Future Visions of X-ray and Gamma Ray Astronomy

Nicholas White

NASA Goddard Space Flight Center

To the Edge of Gravity, Space, and Time . . .

Grand Challenge From the NASA Administrator

"Can you imagine what a stellar black hole would actually look like if you were poised a few thousand kilometers above it?"

"What a legacy that would be for humanity—looking at the event horizon of a black hole!"

"It's time to bring science fiction to reality!"

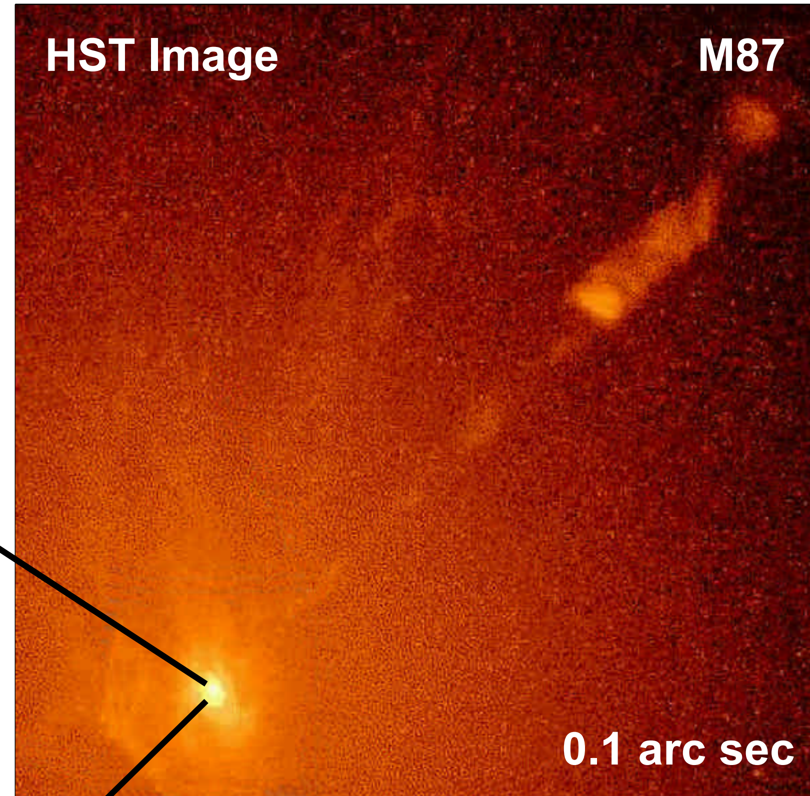
Dan Goldin

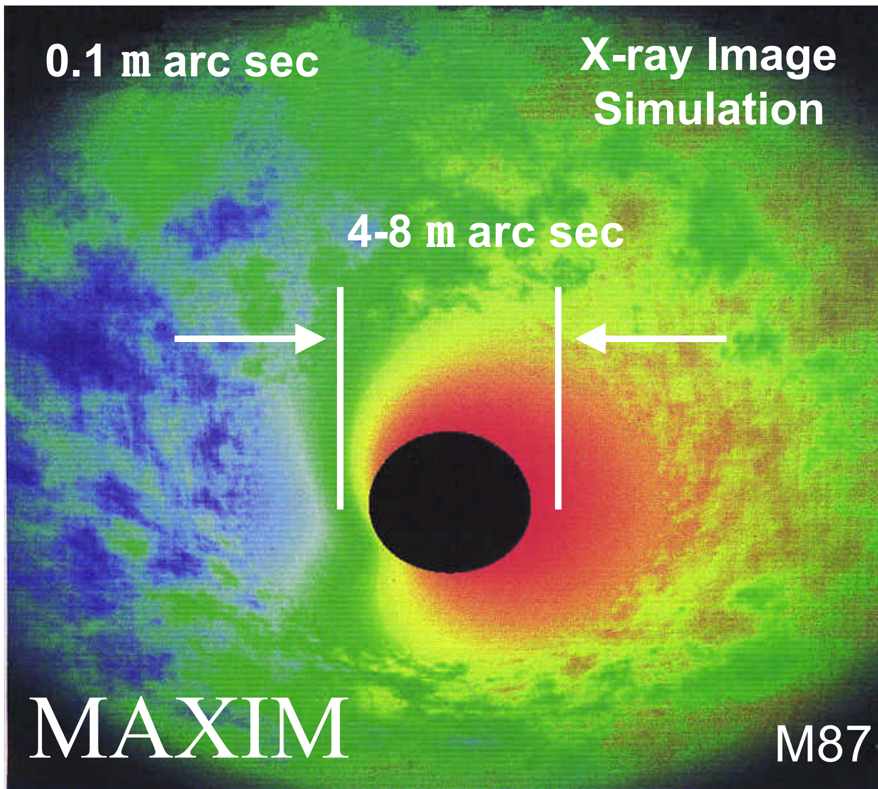
Fermilab Inner Space-Outer Space Conference
May 28, 1999

MAXIM: MicroArcsecond X-ray Imaging Mission

Take direct image of a black hole event horizon

- Ultimate journey to visit a black hole
- Fundamental importance to physics
- Captures the imagination



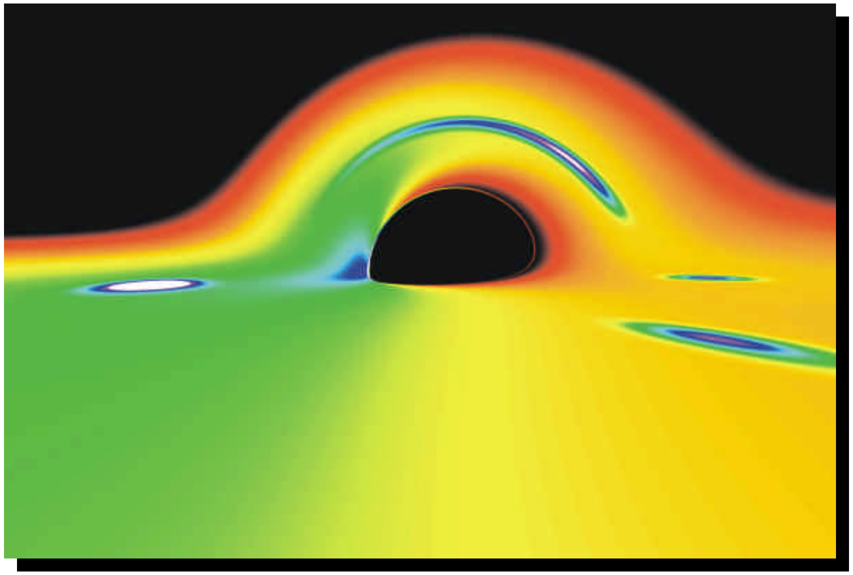


Requires 0.1-1m arc second imaging

X-ray interferometry is the best approach

- Close to event horizon, energy is emitted in X-rays
- Baseline of 20 m at 1 Å for 1 m arc second
- 1-10 million times higher resolution than Chandra!

The Eye of the Beast!



Simulation showing the distortions of space-time Predicted by General Relativity

What we see will depend on black hole spin and viewing angle

- **Black Holes represent an extreme, where:**
  - Space and time cease to exist?
  - The laws of physics break down?
  - The strong gravity limit of GR
  - A place where we can test the laws of physics?

Gravity Reigns Supreme

- **Image a black hole and we may see:**
  - The shadow of the event horizon
  - The final plunge of material towards the event horizon
  - The acceleration zone of cosmic jets
  - Energy release in an accretion disk
  - Perhaps exotic phenomena. . .

- **This will push us to the limits of our technology**
  - *1-10 million times better than current capability!*

Take a step-by-step approach

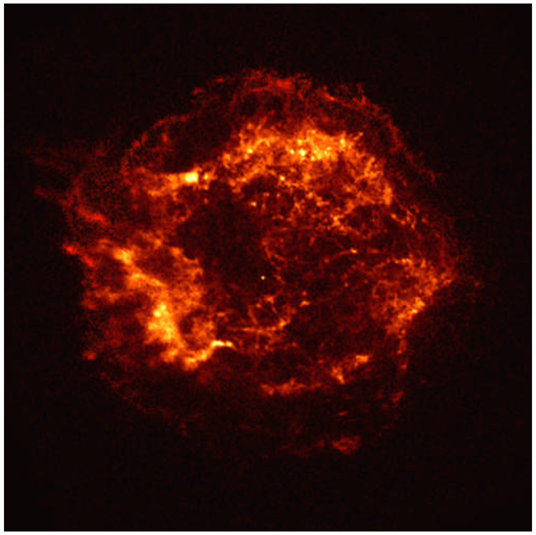
Outline

Two themes to the presentation

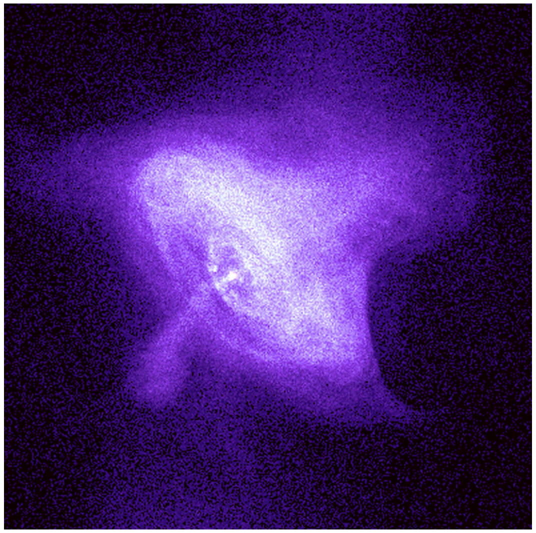
- **Image a Black Hole**
  – How can it be done?
  – Outline a Roadmap to do it
  – Discuss some of the science possibilities along the way

- **High Energy Cosmology**
  – Large scale structure in the Universe
  – The nature of dark matter
  – Missing baryon problem
  – Observing the first black holes and starbursts
  – Nucleosynthesis and the creation of the elements

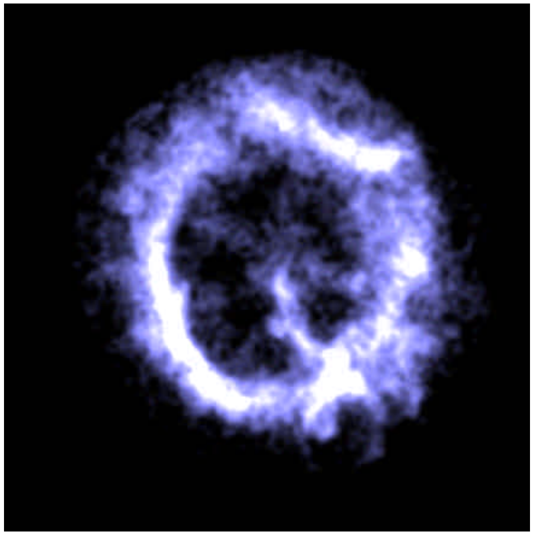
The Excitement of Chandra!



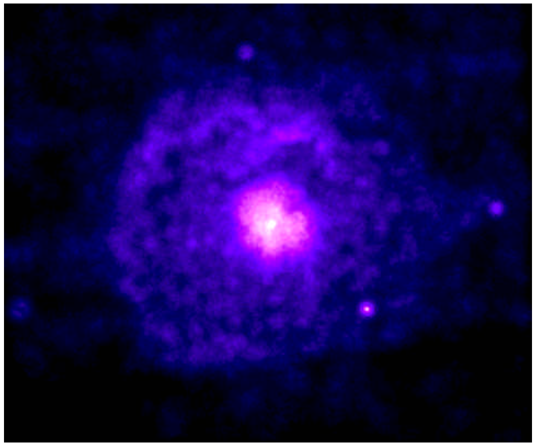
Cas A SNR



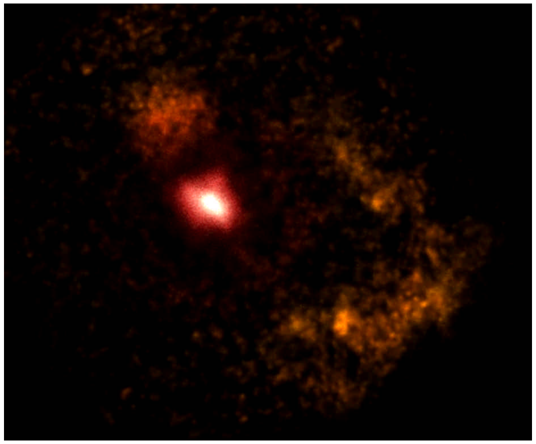
Crab SNR



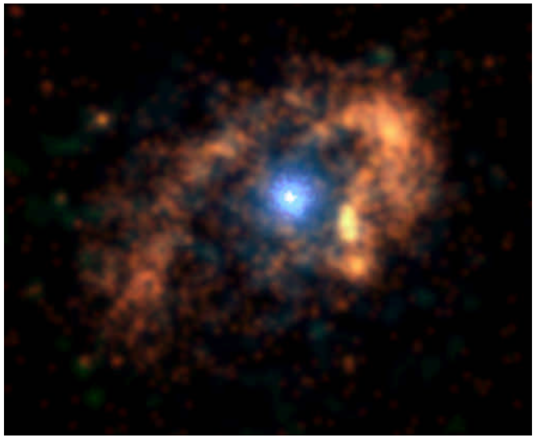
E0102-72 SNR in Tuc



G21.5-0.9 SNR in Sct



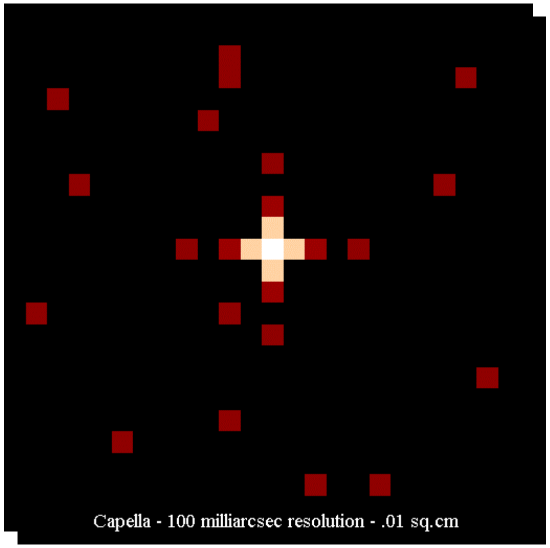
PSR 0540-69 Pulsar/SNR in Dor

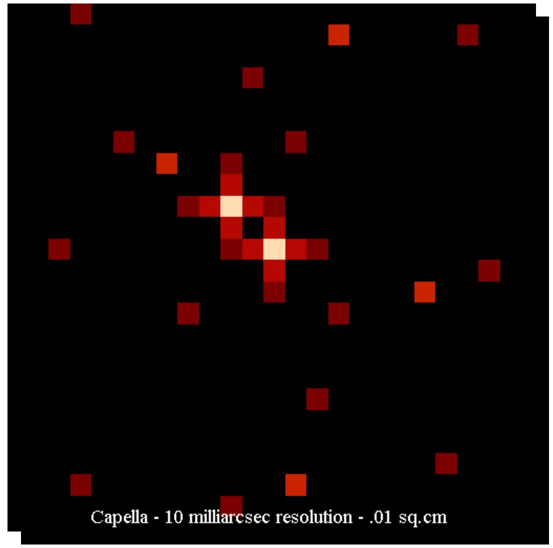


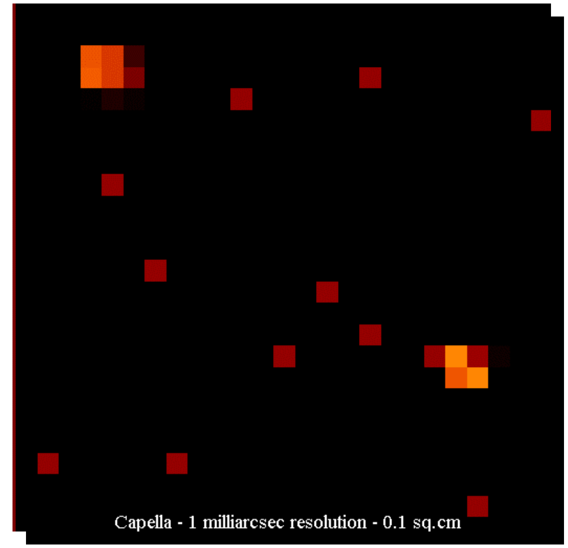
Eta Carina

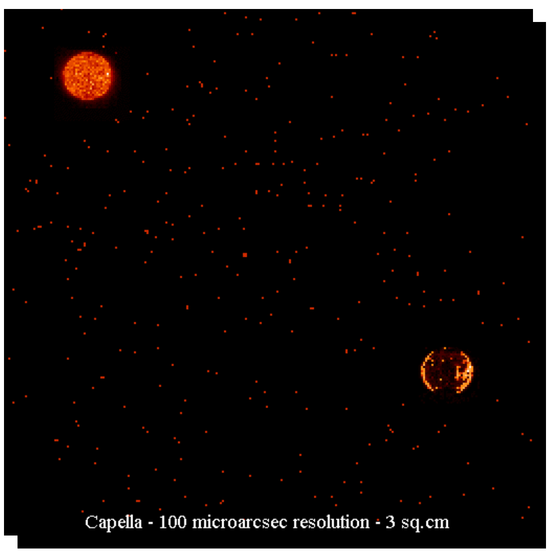
Credit: Chandra X-ray Observatory

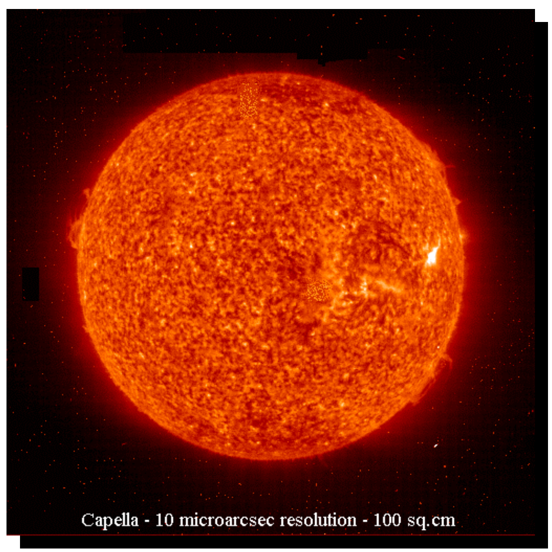
Power of Angular Resolution: Visiting Capella

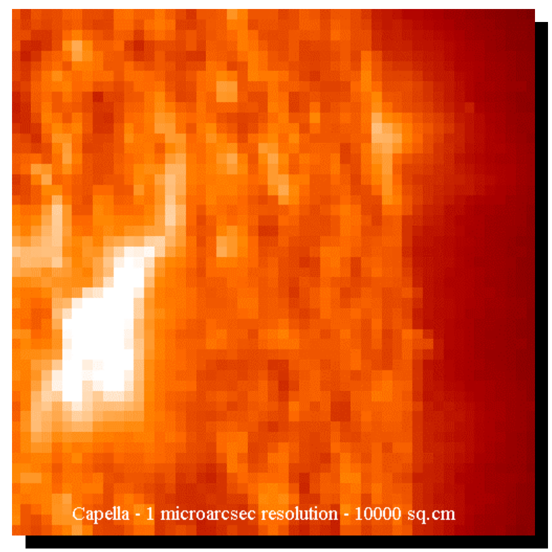

Capella - 100 milliarcsec resolution - .01 sq.cm


Capella - 10 milliarcsec resolution - .01 sq.cm


Capella - 1 milliarcsec resolution - 0.1 sq.cm


Capella - 100 microarcsec resolution - 3 sq.cm


Capella - 10 microarcsec resolution - 100 sq.cm


Capella - 1 microarcsec resolution - 10000 sq.cm

Credit: Webster Cash

Black Hole Parameters

- **Black Holes have three parameters:**
  - Mass, spin, and charge
  - Only mass and spin are observable
- **Radius of event horizon depends on spin**
  - Maximally rotating hole has a factor 2 smaller radius
- **Mass can be inferred**
  - Dynamics (HST)
  - Observe reverberation effects from flares
- **Spin can also be inferred**
  - X-ray Iron K line
  - Spectra

Which are the Best Black Hole Targets?

- **AGN in nearby galaxies: (a few to 17 Mpc)**

  more certain, larger masses, larger angular sizes (2–6 mas)

  but

  usually weak X-ray sources (< 0.1–3) ´ 10^{-12} ergs cm^{-2} s^{-1}

- **Nearby AGN: (20 - 150 Mpc)**

  less certain, smaller masses, smaller angular sizes (~ 0.1–0.2 mas)

  but

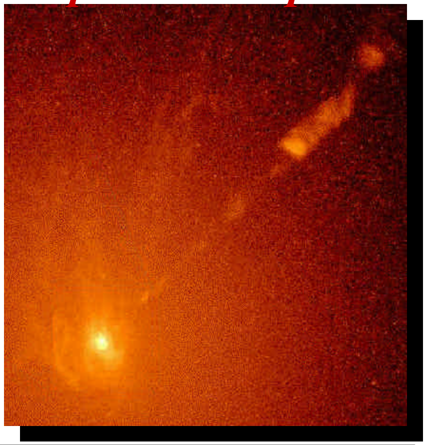
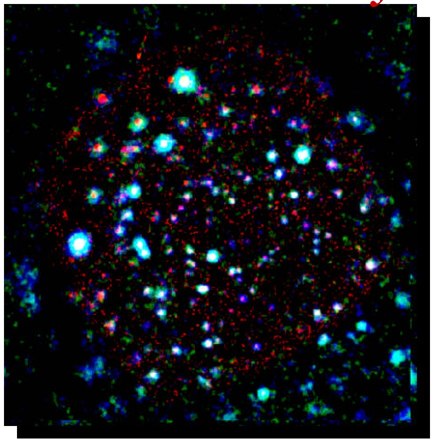
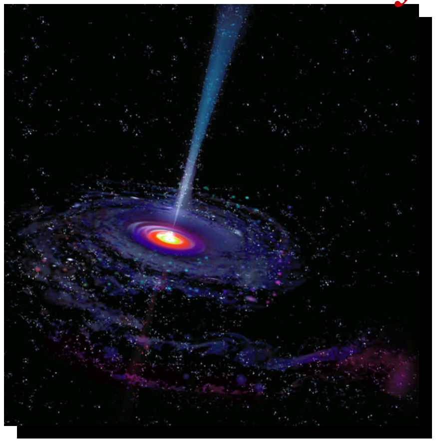
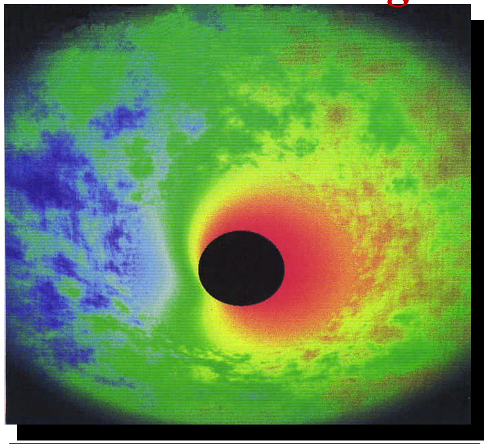
  “strong” X-ray sources (20–100 ´ 10^{-12} ergs cm^{-2} s^{-1})

- **Galactic Center**
  - **2.6 ´ 10^{6} $M_{\odot}$, 6.5 to 13 mas**
  - **Flux uncertain 14 ´ 10^{-12} ergs cm^{-2} s^{-1}**

- **Galactic black holes are too small (~100 pico-arc sec)**

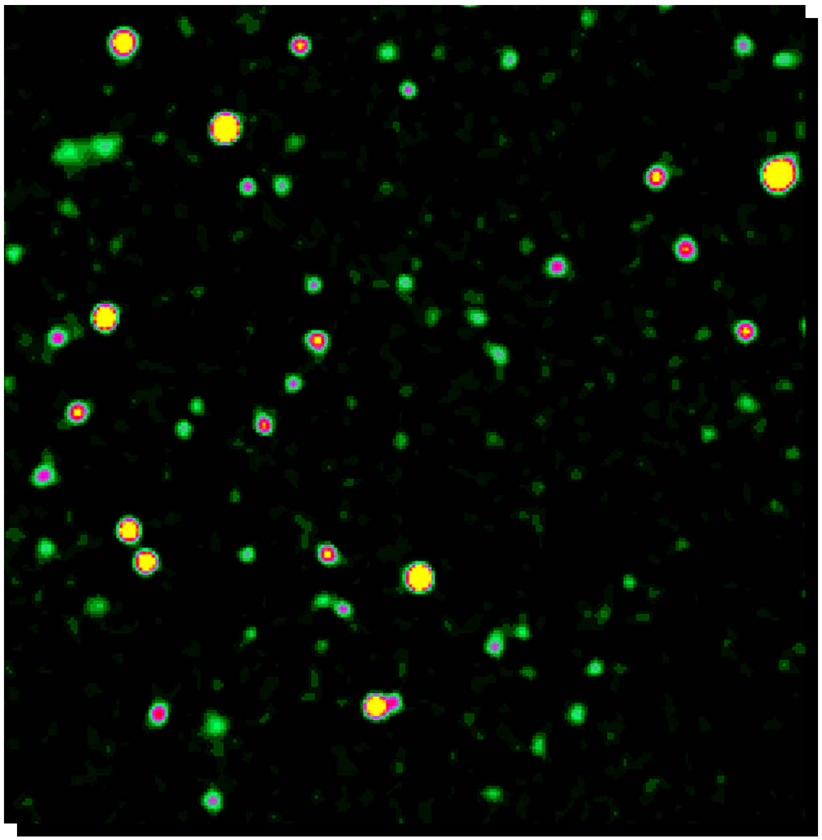
Need Chandra and Constellation-X to demonstrate feasibility, identify best targets, and optimize MAXIM parameters.

Search for New Physics: Journey to a Black Hole

1990-1999	2000-2010	2007-2020	2015-2025
Do black holes exist?	Where are They?	How do they evolve?	How do they work?
Explore All Options	*Black Hole Survey*	*Black Hole Anatomy*	*Take a Direct Image*
			
ASCA ROSAT HST CGRO RXTE	Chandra XMM Astro-E INTEGRAL GLAST EXIST	Constellation-X LISA GLAST EXIST Generation-X	MAXIM ARISE

Where are they?: X-ray Surveys

Thirty-five years after discovery of the Cosmic X-ray Background, ROSAT has resolved into discrete sources ~80% of the background at 1 keV



25′

Constellation-X will be able to take detailed high resolution spectra for all of the sources pictured here.

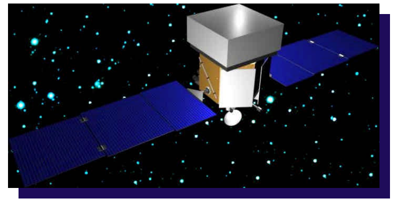
- ROSAT Deep Field was (up until the launch of Chandra) our deepest look at the X-ray sky
- Optical identification programs reveal that most are AGN at a mean redshift of 1.5
  - **Reaching out to redshifts as high as 4**
  - **All these sources are black holes!**
- ASCA and BeppoSAX show evidence for absorbed population of AGN

Up to one million super massive black holes (AGN) will be discovered by Chandra and XMM

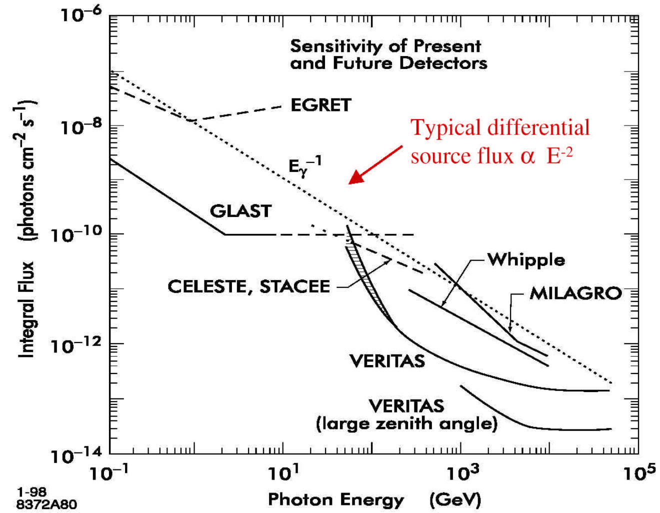
Gamma-ray Large Area Space Telescope

A new mission to study high energy cosmic gamma rays
in the energy range 20 MeV - >300 GeV

Capabilities:



- Huge FOV (~20% of sky)
- Broadband (4 decades in energy, including unexplored region > 10 GeV)
- Unprecedented PSF for gamma rays (factor > 3 better than EGRET)
- Large effective area (factor > 4 better than EGRET)
- Results in factor > 30-100 improvement in sensitivity
- No expendables: long mission without degradation
- Launch in 2005



Large overlap with ground-based experiments (see Topic III talk by Vassiliev), with comparable sensitivity and complementary capabilities.

GLAST draws the interest of both the HEP and HEA communities.

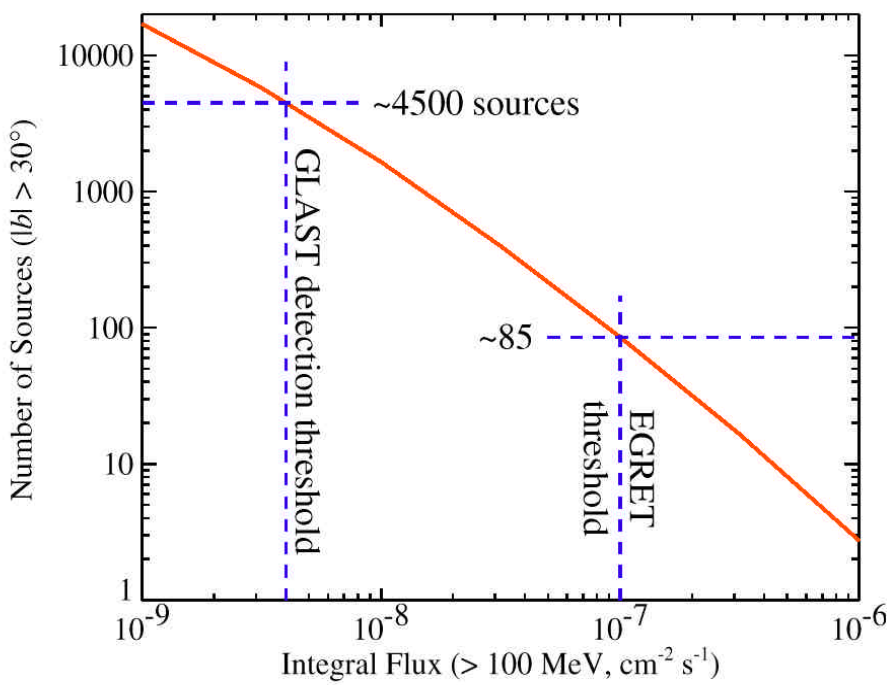
What GLAST will do

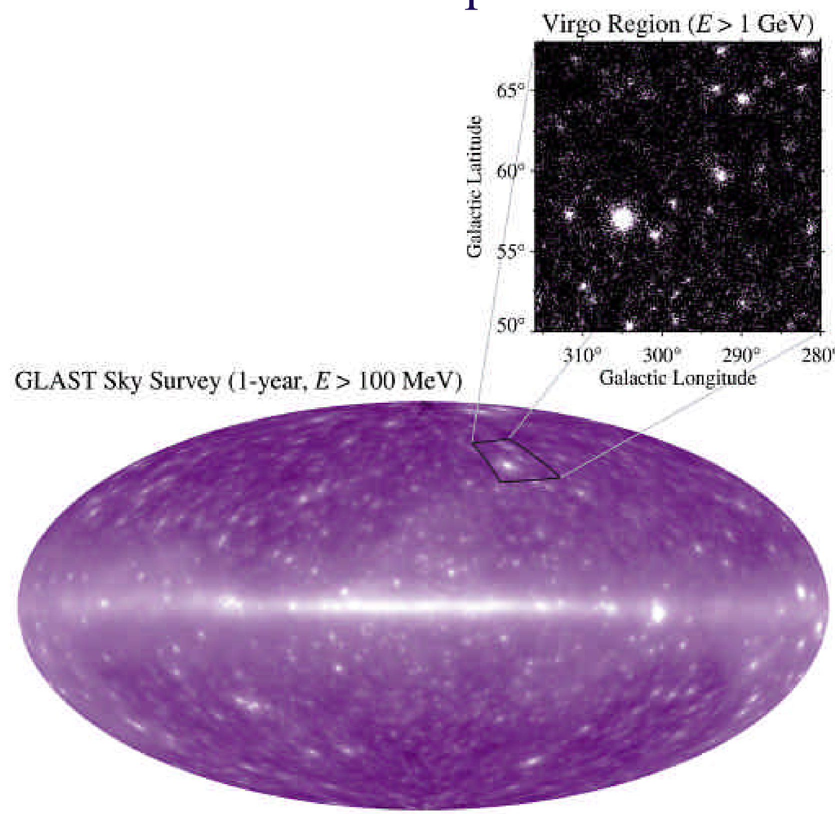
- Solve the current unidentified source problem—localization to arcmin scale
- AGN—high latitude point source sensitivity ($<4 \times 10^{-9}$ cm^{-2} s^{-1}) implies thousands of blazars will be detected and studied
- Deep full-sky surveys
- Test origin of extragalactic diffuse as unresolved sources
- Probe via spectral cut-off optical-UV EBL in era of galaxy formation
- Galactic particle dark matter searches
- SNRs and cosmic ray acceleration—resolve shock acceleration region spatially and spectrally
- High energy behavior of gamma-ray bursts
- Pulsars—population studies, test acceleration models via spectral roll-offs

Expect GLAST era to stimulate broad community interest in gamma-ray data

GLAST and Blazars

- Statistically accurate calculation of blazar contribution to the high energy diffuse extragalactic background
- Constrain jet acceleration and emission models
- Multi-wavelength monitoring of blazars
- Measure spectral cut off with distance for a large sample of sources to redshift z > 4
  - Attenuation of AGN flux at high energy due to interactions with optical-UV extragalactic background light





Beyond GLAST

GLAST represents a very large jump in capabilities in a relatively unexplored window, so it is difficult to guess what questions will be interesting next. (Hopefully NOT what we are thinking now.)

What GLAST won't do

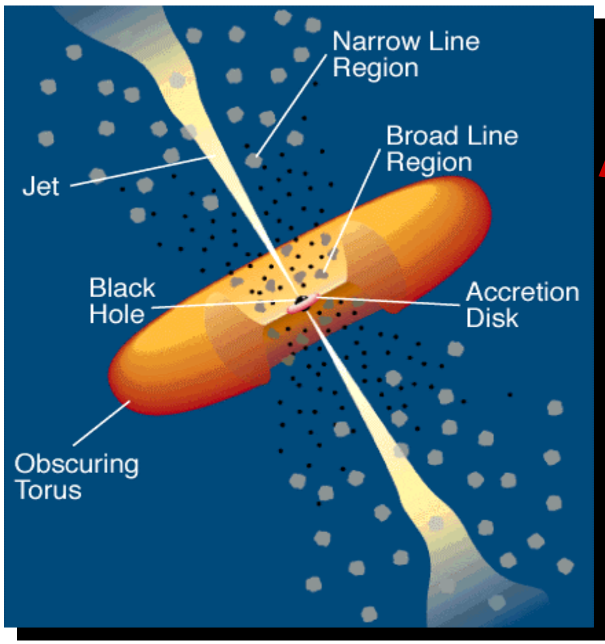
- Polarization measurements (not excluded, but difficult)
- Image an AGN in gamma rays

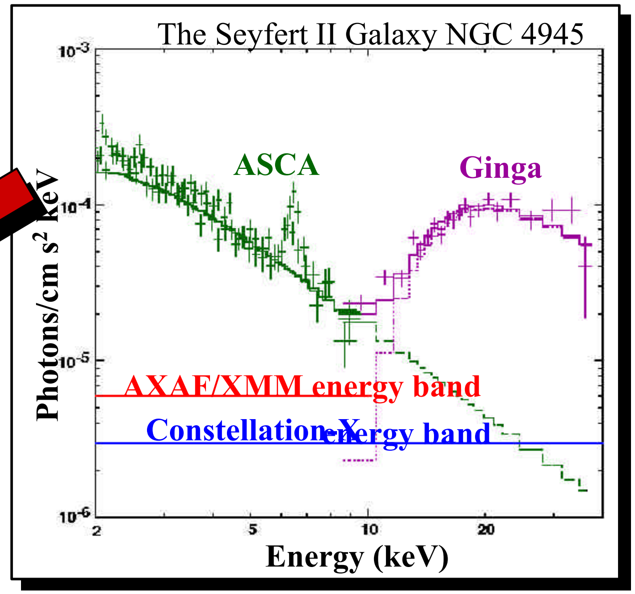
Great leaps in angular resolution and area are likely to be necessary, even if not for a survey instrument (i.e., small FOV may be OK).

There are no obvious breakthrough technologies on the horizon. An opportunity for new ideas!

Obscuration of AGN

Increasing evidence that there is a large population of highly absorbed AGN that may be responsible for the X-ray background





AGN viewed edge-on through the optically thick torus

Only visible above 10 keV where current missions like Chandra have poor sensitivity

Swift and then EXIST will provide first sensitive surveys of the 10-500 keV band

Constellation-X will use multi-layer coatings on focusing optics to increase sensitivity at 40 keV by >100 over RXTE

EXIST

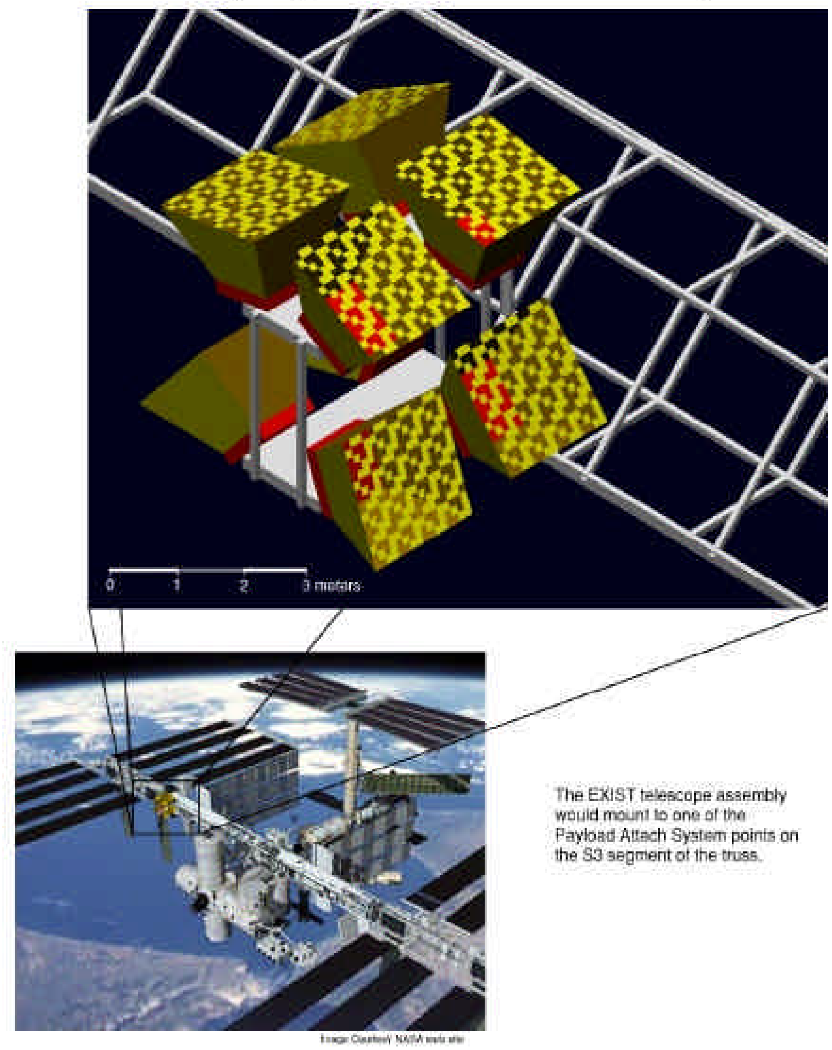
All Sky Imaging Deep Hard X-ray Survey

- **Science:**
  - All-sky survey of obscured black holes in AGN
  - Gamma-Ray Bursts out to z ~ 30
  - Soft Gamma-Ray repeaters in Local Group
  - Black Hole X-ray transients in the galaxy
  - SN rate in Galaxy

- **Mission:**
  - 8 coded aperture CZT telescopes (each 40deg FOV; 1 m^2)
  - International Space Station attached payload
  - ~ 0.05 mCrab to ~ 10-100 keV; ~ 0.5 mCrab to 600 keV
  - All-sky imaging each 90 min orbit
  - 5' resolution; ~ 10"–1' positions
  - Energy resolution E/DE ~ 30–100

Energetic X-ray Imaging Survey Telescope (EXIST) on ISS

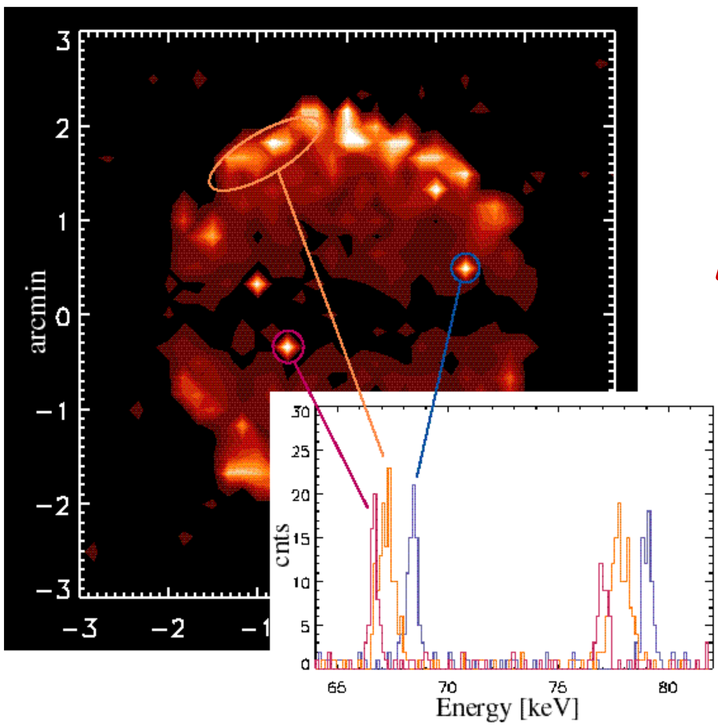
Conceptual Layout of EXIST on ISS Integrated Truss Assembly



Credit: Josh Grindlay

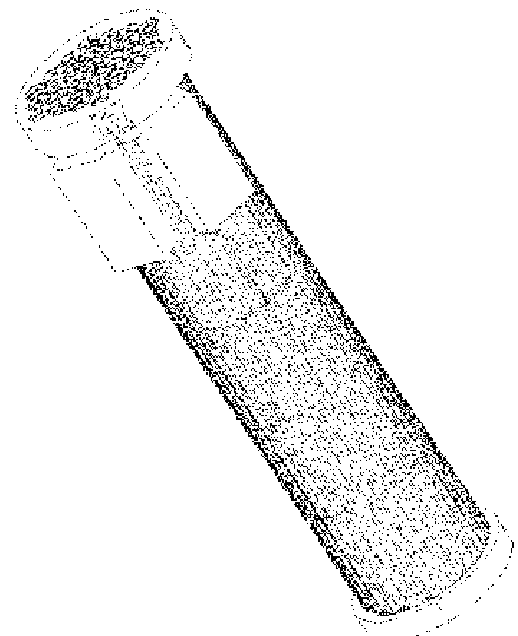
High-Resolution Spectroscopic Imager (HSI)

- Employs grazing incidence *multilayer* optics and Germanium detectors in the 5–200 keV band to achieve a factor > 100 sensitivity improvement over INTEGRAL - *technology enabled by Constellation-X development*
- High spatial (20") and spectral resolution mapping of the ^{44}Ti line in remnants
- Optimized for high sensitivity measurement of the evolution of key prompt lines in Type Ia SNe beyond Virgo



Simulation of a 105 s observation of Cas A in 44Ti. The line shifts can be mapped on fine spatial scales.

Precursor to wide FOV, large area Advanced Compton Telescope (ACT)



Credit: Fiona Harrison

“X-ray Roadmap” to Image a Black Hole

Imaging

ROSAT
Einstein

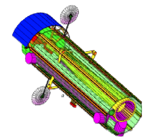
Chandra

100-1000 cm^2
0.5 arc sec

Optimize MAXIM Parameters

1000 times finer imaging

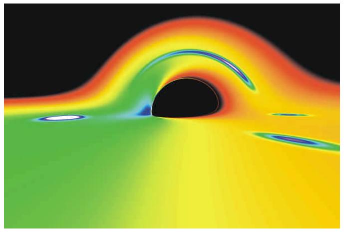
MAXIM Pathfinder



100 cm^2
2 m baseline
100 µarc sec

Million times finer imaging

MAXIM



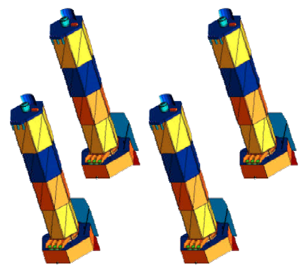
1000 cm^2
100-1000 m baseline
100 nas

Spectroscopy

ASCA
RXTE

XMM
Astro-E

Constellation-X



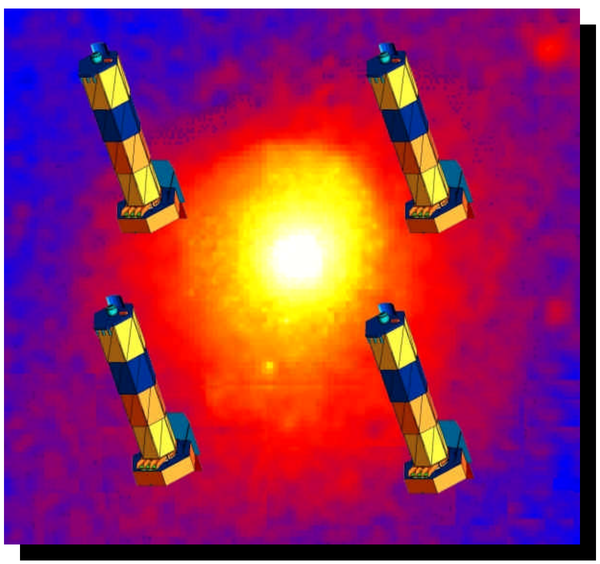
3 m^2
Indirect imaging via spectroscopy

Do they exist?	*Where are they?*	*Conditions in the inner disk*	*X-ray Interferometry Demonstration*	*Black hole Imager!*
	2000	*2008*	*2014*	*2020*

The Constellation X-ray Mission

o **Key scientific goals**

- Black hole parameters and environment
- Observe formation and evolution of large scale structure in the Universe
- Plasma diagnostics and elemental abundances from stars to clusters



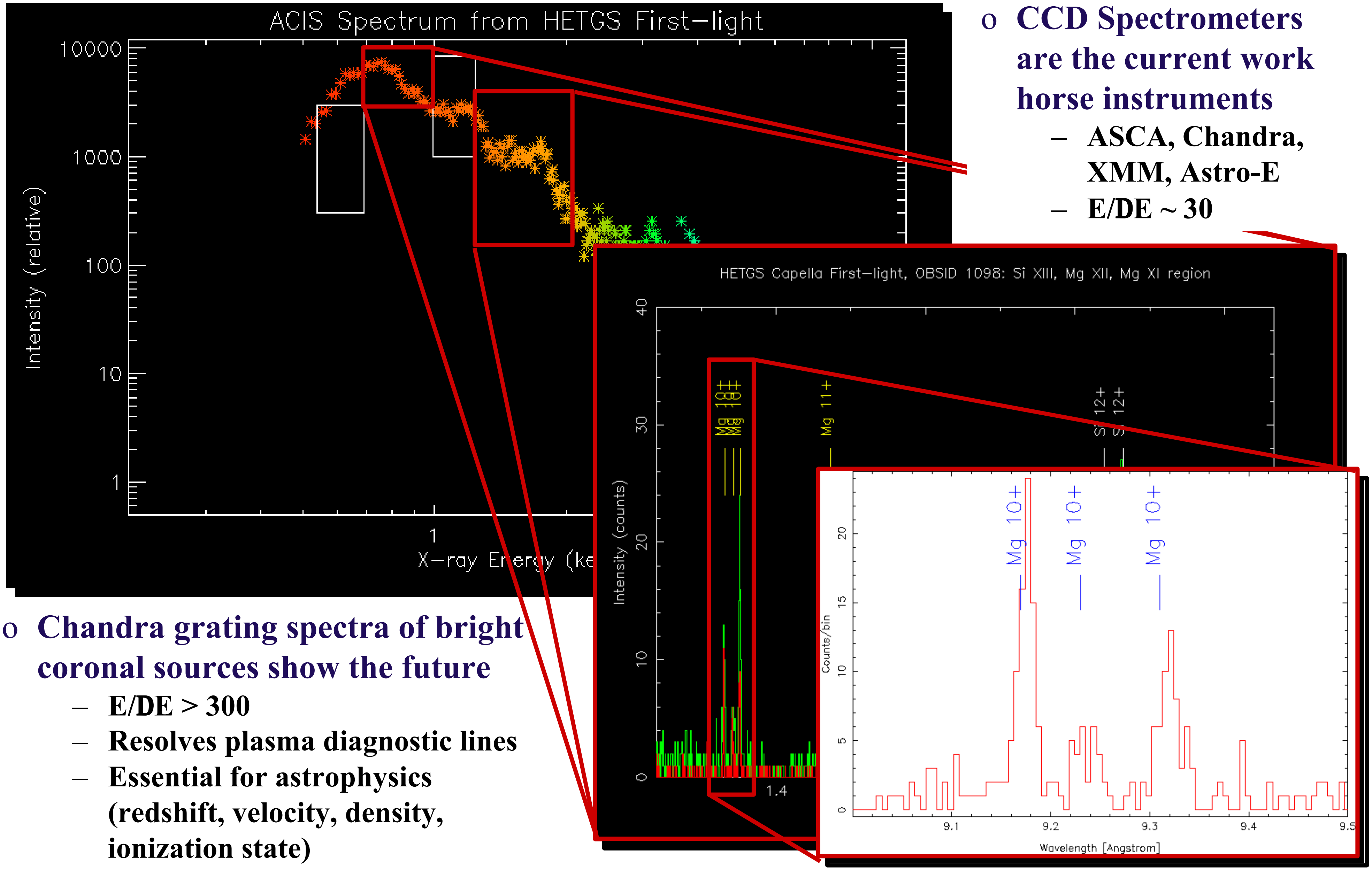
An X-ray Keck Observatory

o **Mission parameters**

- **Effective area:** 15,000 cm^2 at 1 keV
  100 times Chandra and XMM for high resolution spectroscopy
- **Spectral resolving power:** 3,000 at 6.4 keV
  5 times Astro-E calorimeter
- **Band pass:** 0.25 to 40 keV
  100 times more sensitive than RXTE at 40 keV

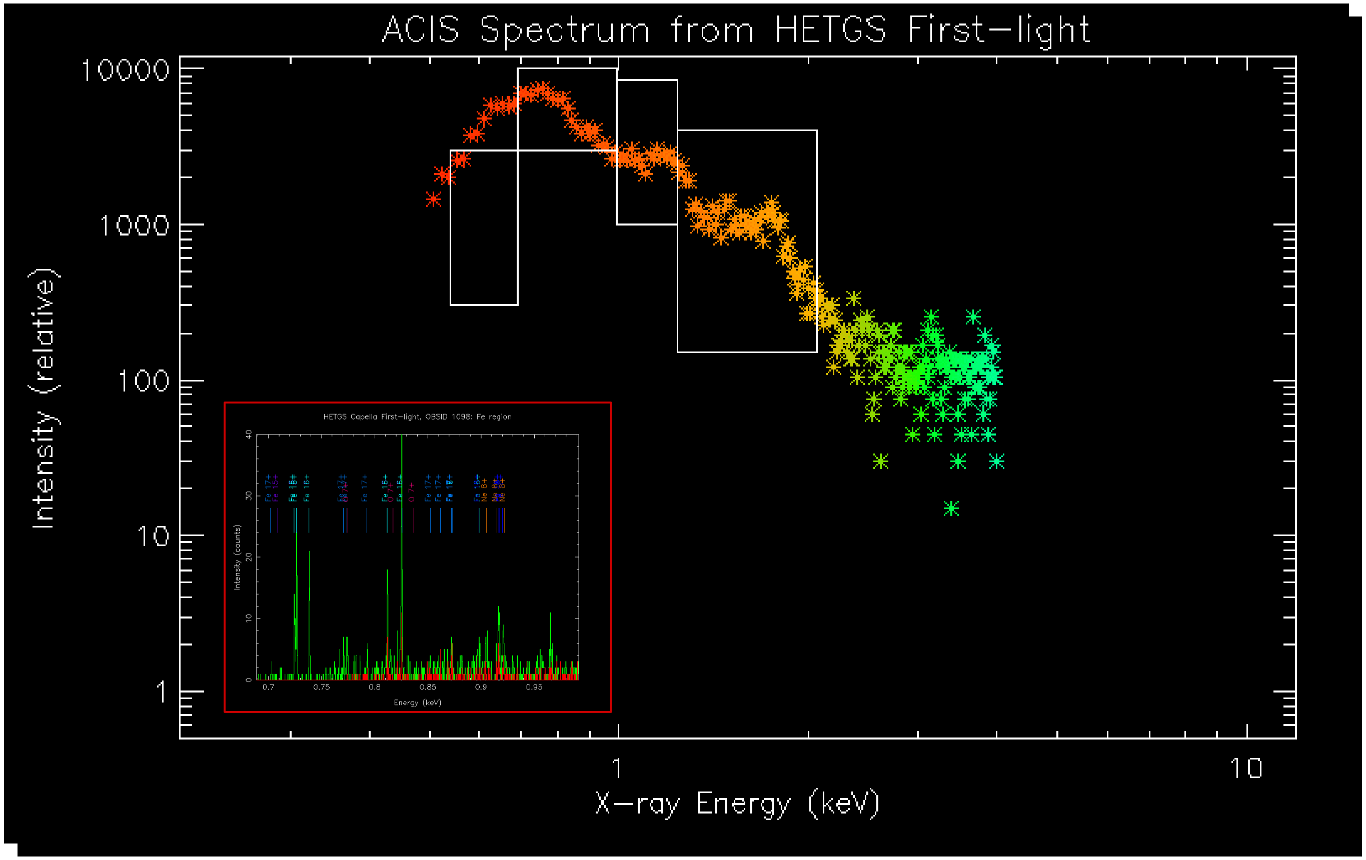
Chandra X-ray Spectroscopy!

- CCD Spectrometers are the current work horse instruments
  - ASCA, Chandra, XMM, Astro-E
  - E/DE ~ 30



- Chandra grating spectra of bright coronal sources show the future
  - E/DE > 300
  - Resolves plasma diagnostic lines
  - Essential for astrophysics (redshift, velocity, density, ionization state)

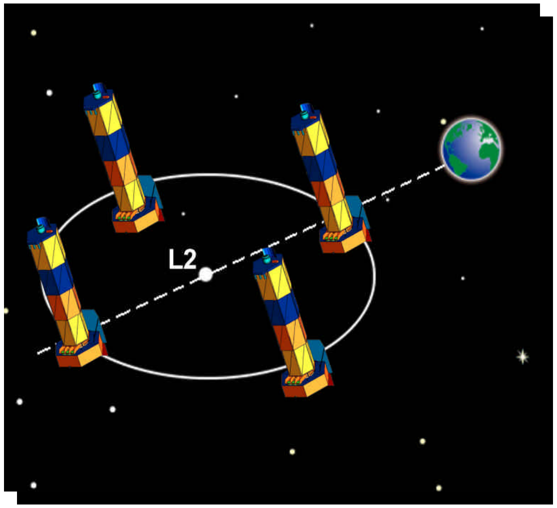
X-ray Astronomy becomes X-ray *Astrophysics*



- The 0.25 to 10 keV X-ray band contains the K shell lines for all of the abundant metals (carbon through zinc) and the L shell lines of most.
- X-ray line spectra are rich in density, temperature, and ionization state plasma diagnostics

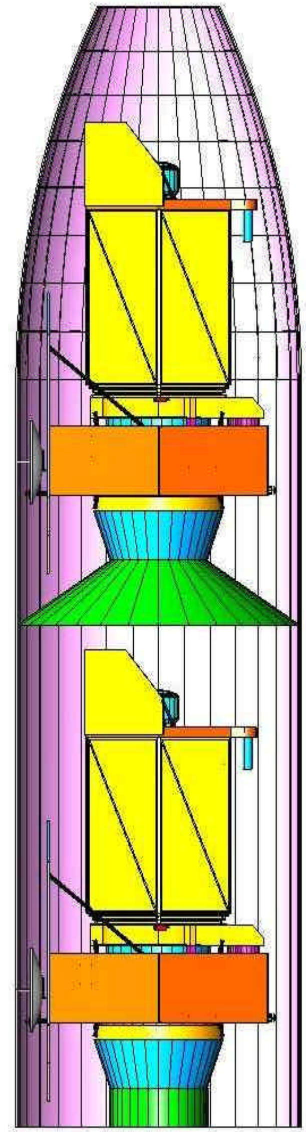
- Energy resolution of CCDs not sufficient to exploit these diagnostics
  - gratings and mircocalorimeters can provide required resolution (E/ΔE) ≥300
  - factor of 100 increase in collecting area over Chandra, XMM, and Astro-E required to reach faint populations

Constellation-X Mission Concept



A multiple satellite approach

- Low-risk approach utilizes a constellation of multiple identical low-cost satellites; each carries a portion of the total effective area
- Simultaneous viewing and high efficiency facilitated by using libration point orbit



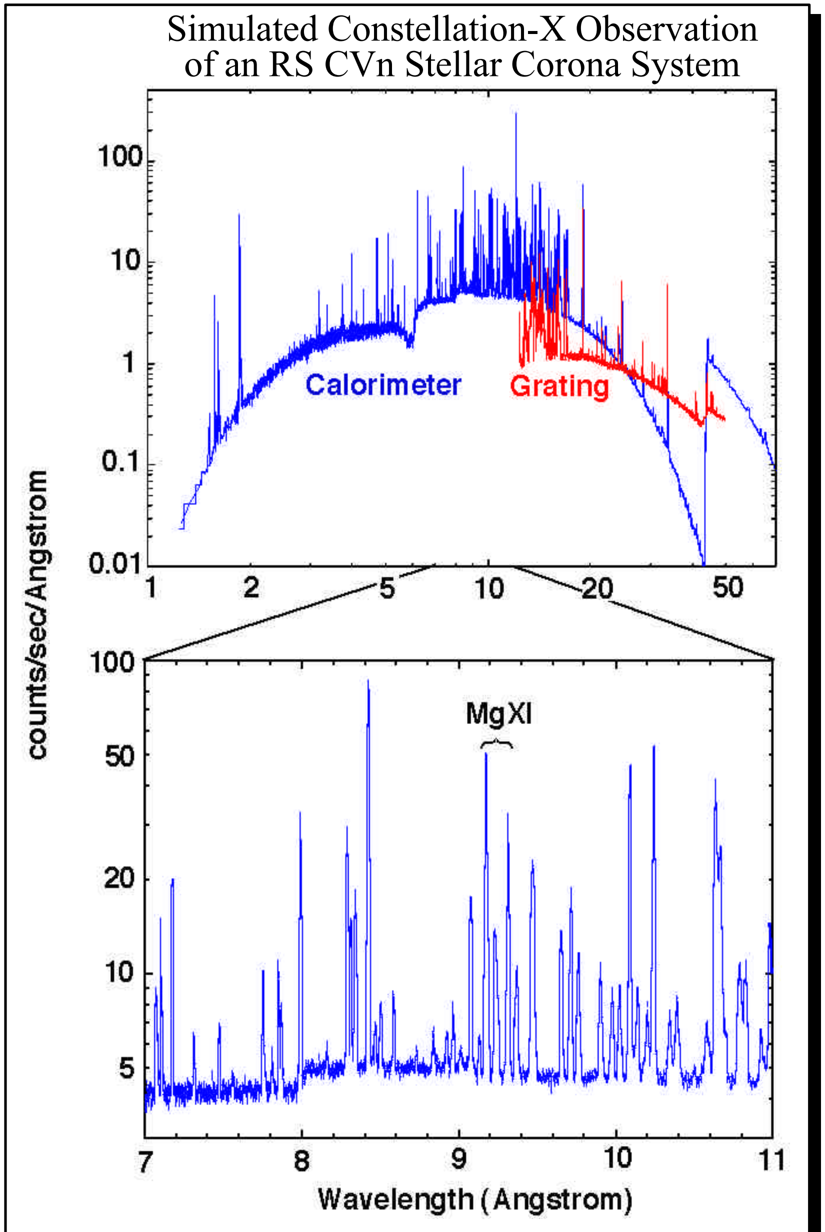
Reference configuration

- Four satellites, launched in 2008–2009 two at a time on Atlas V or Delta IV
- Extendible optical bench achieves a focal length of 10 m on-orbit
- Modular design allows parallel development and use of low cost standard bus architecture and components

Technology development

- Lightweight, high throughput X-ray optics
- Calorimeters with 2eV resolution
- Long-lived 2-6K cryo-coolers
- Hard X-ray optics and detector
- CCD and Gratings

X-ray Astrophysics with the Constellation X-ray Mission

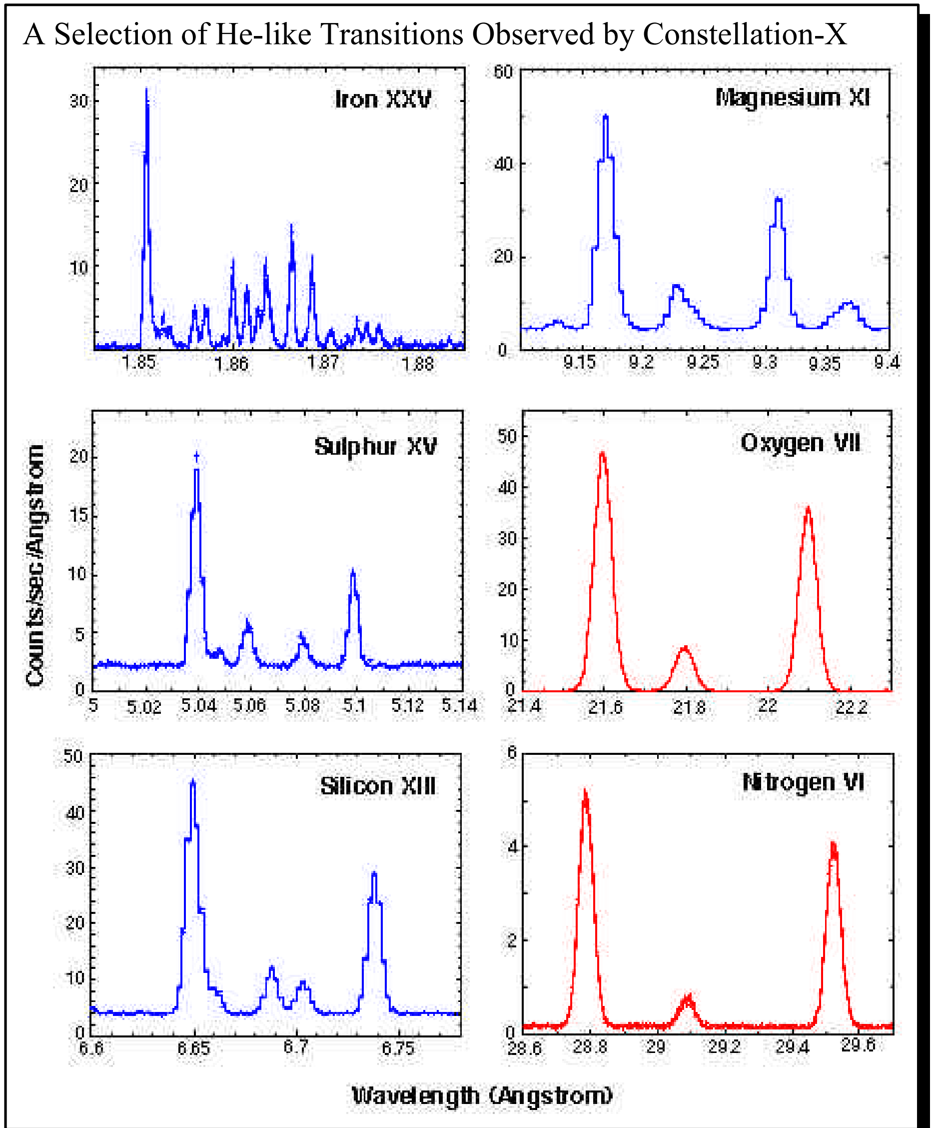


The Constellation-X energy band contains the K-line transitions of 25 elements

The sensitivity of Constellation-X will allow abundance, measurements and plasma diagnostics in:

– Intergalactic medium
– Intracluster medium
– Halos of elliptical galaxies
– Starburst galaxies
– Supernova remnants
– Interstellar medium
– Stellar coronae
– Young and pre-main sequence stars
– X-ray irradiated accretion flows

Temperature, Density, and Velocity Diagnostics



The spectral resolution of Constellation-X is tuned to study the He-like density sensitive transitions of Carbon through Zinc

Direct determination of

- Densities from 10^8 to 10^{14} cm^{-3}
- Temperature from 1-100 million degrees.

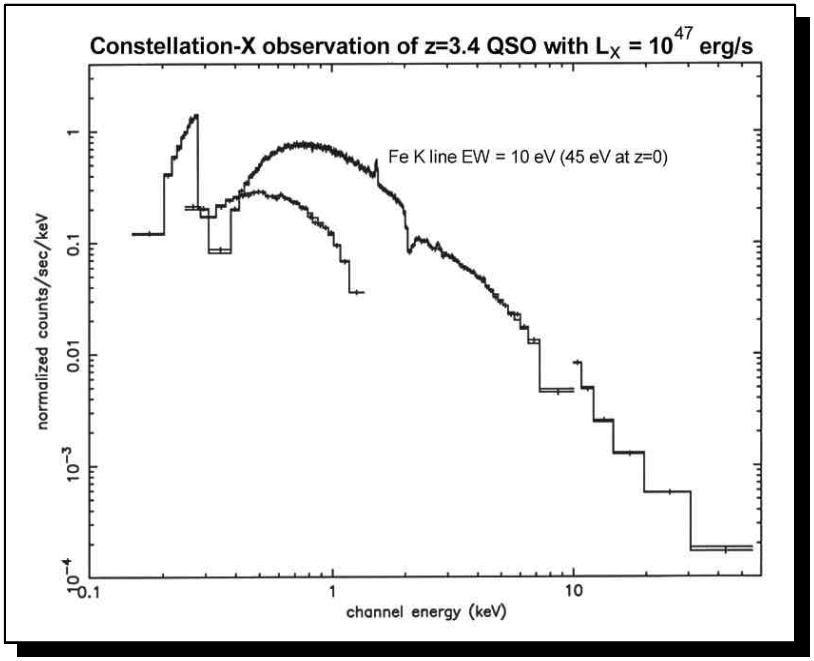
Velocity diagnostics at Fe K line:

- Line width gives a bulk velocity of 100 km/s
- Line energy gives an absolute velocity determination to 10 km/s

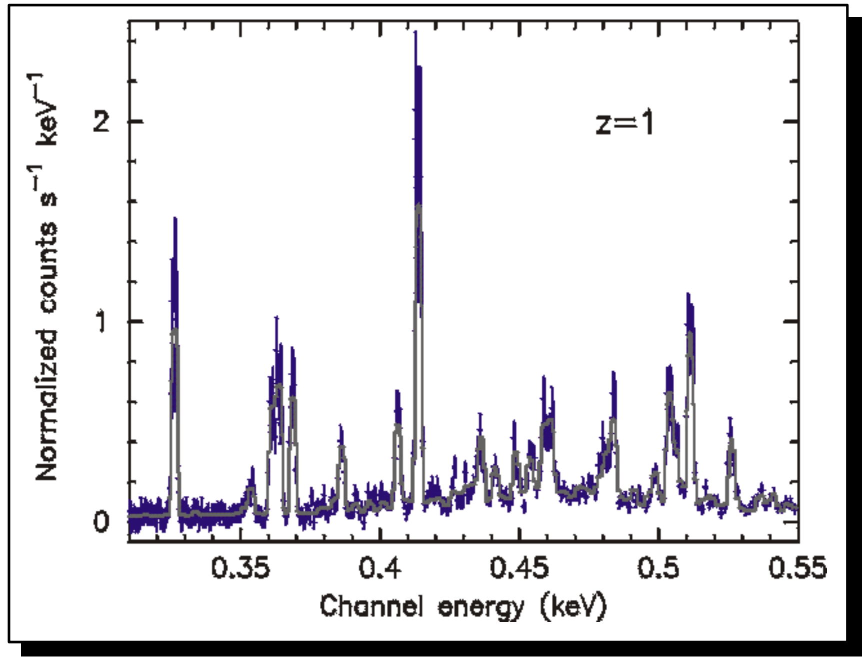
Simultaneous determination of the continuum parameters

- Crucial for abundance determinations
- Identify non-thermal components

Super Massive Black Holes at High Redshift



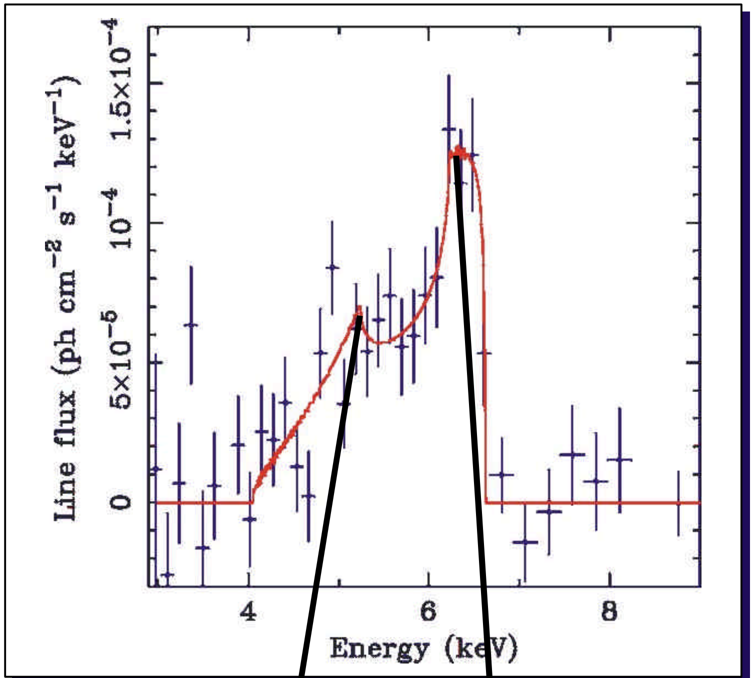
Constellation-X grating, calorimeter, and HXT simulation of a quasar at z = 3.2.

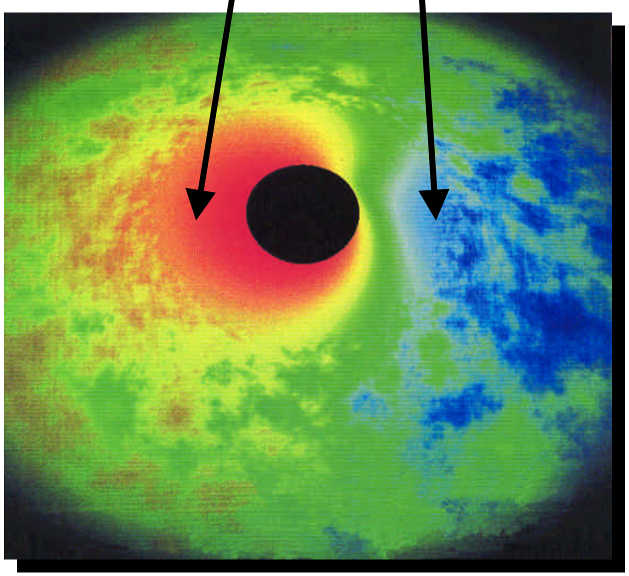


A 100 ks grating simulation of a starbursting Seyfert galaxy at z = 1.

- o Study faint AGN populations
- o Understand the role black holes play in galaxy evolution
- o Examine the starburst-AGN connection

Indirect Imaging of Black Holes Using Spectroscopic Deconvolution



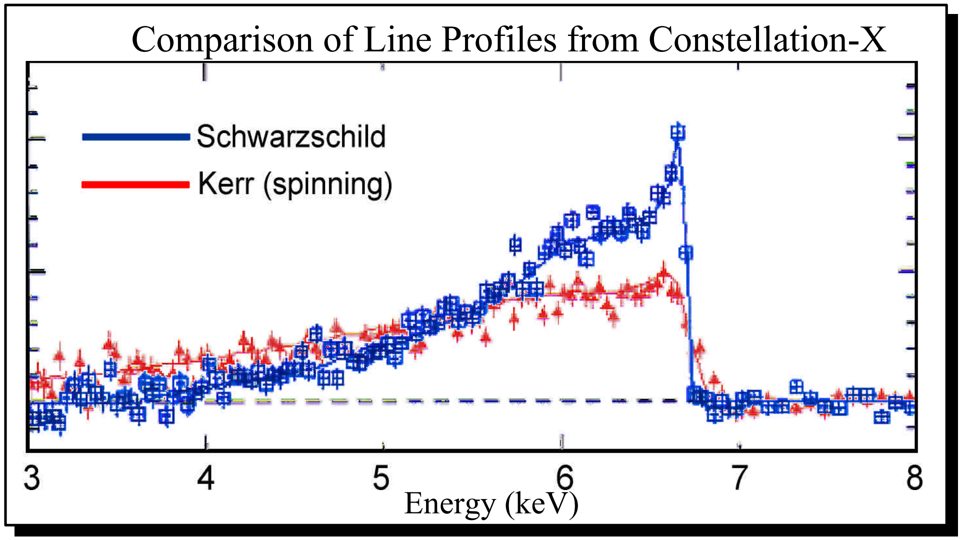


- ASCA has discovered relativistically broadened iron K-a lines that come from close to the event horizon

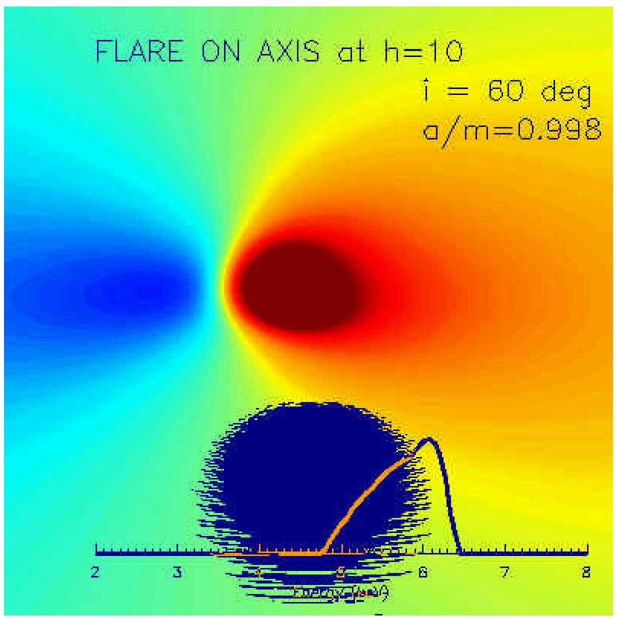
- This line provides a unique probe of the inner sanctum near black holes, observing the effects of GR in the strong gravity limit

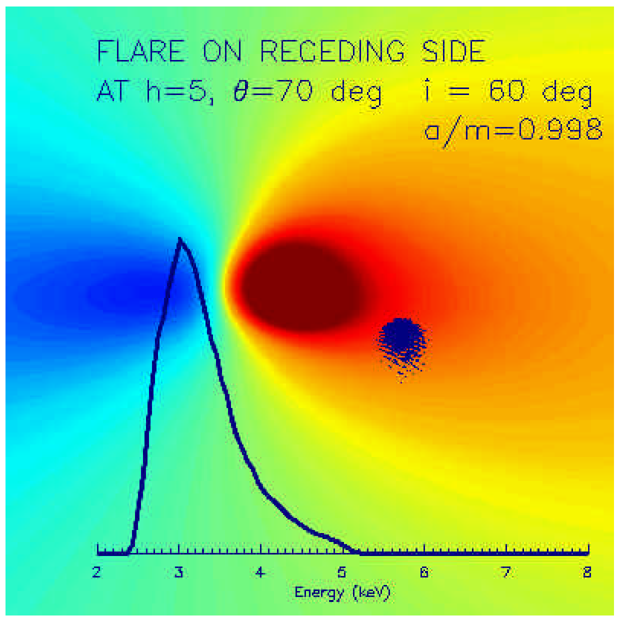
- Much larger collecting area and improved energy resolution required to exploit this diagnostic
  - Constellation-X is designed for this

Constellation-X Relativistic Iron K Line Diagnostic



- Constellation-X will determine black hole mass and spin using iron K-a lines
  - Spin from the line profiles
  - Mass from the time-linked intensity changes for line and continuum emission
  - Reconstruct via deconvolution of the line profile "images" of inner disk



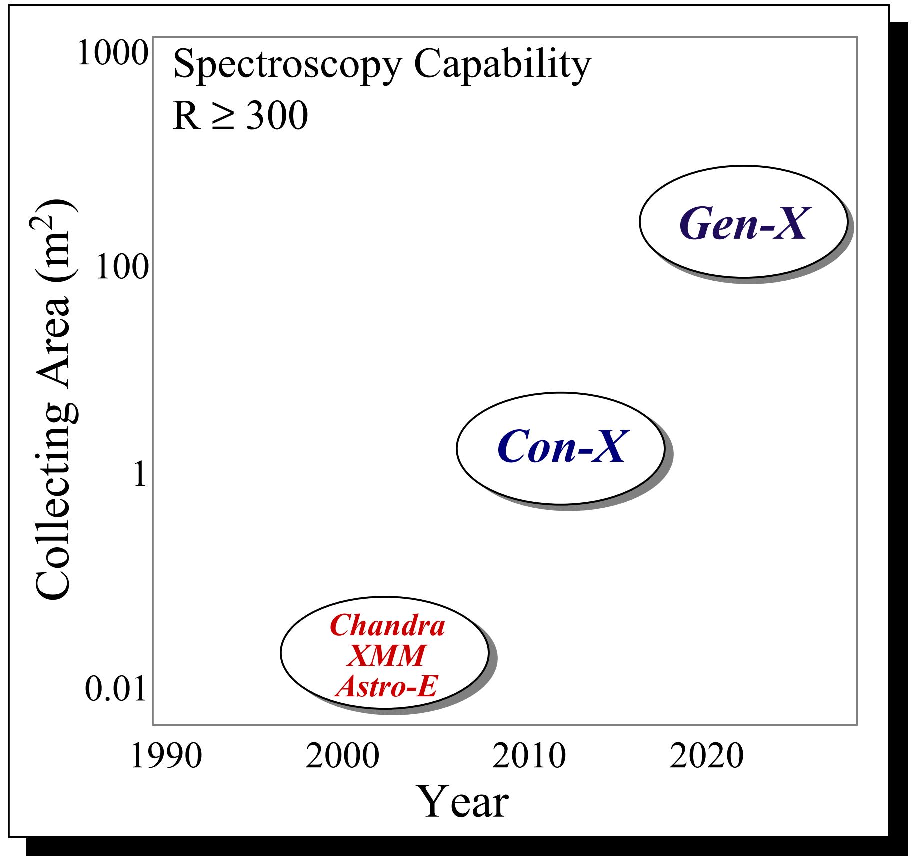


Generation-X:
A Future Ultra-Large Aperture X-ray Telescope

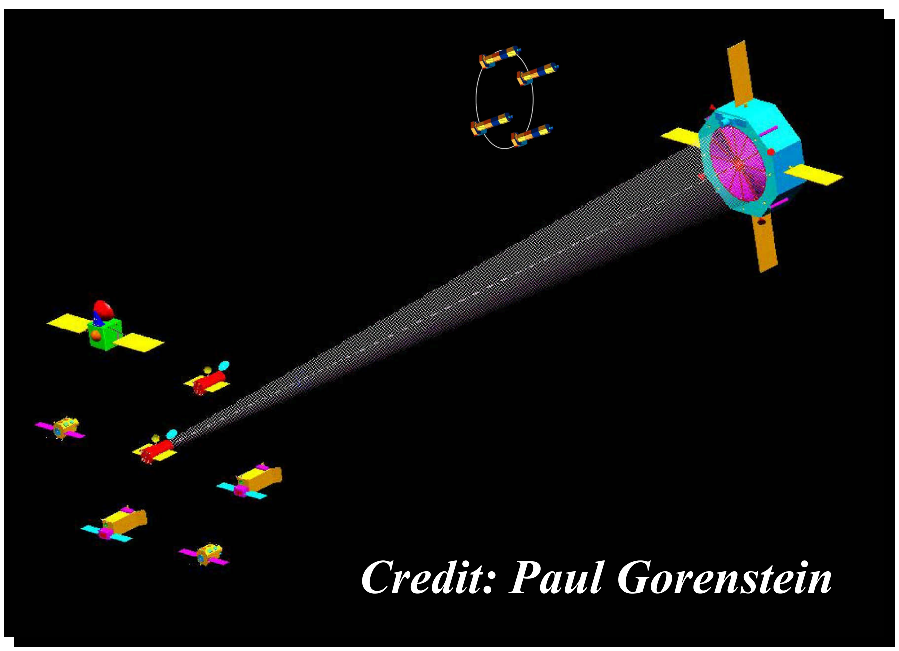
The Universe at redshift >5

- The formation of the first black holes
  - Black hole mass ~ 1 million solar masses?
- The first Starburst Galaxies
  - Winds and outflows as galaxy forms

Need to reach ~10^{41} erg/s at z = 5

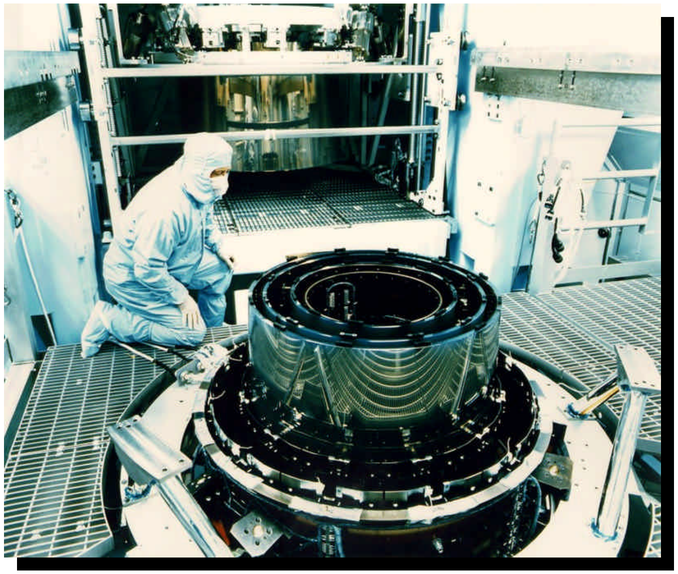


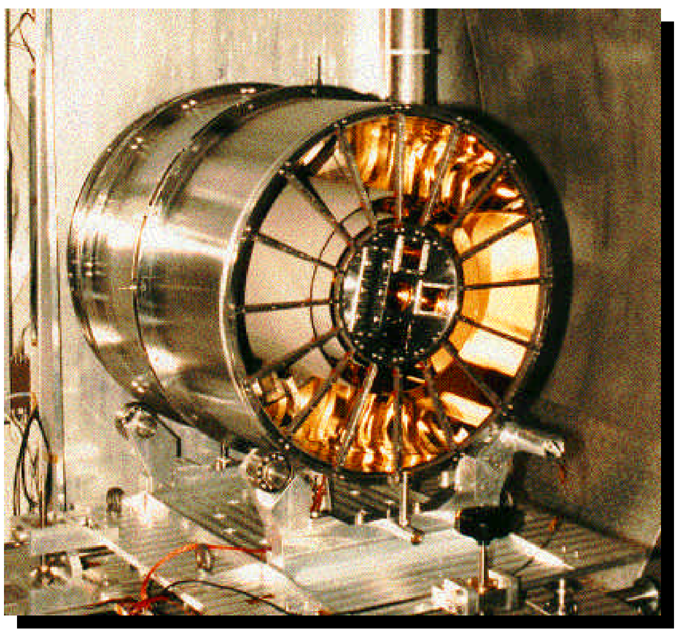
Spectroscopy 100 times fainter than Constellation-X



Equivalent of 30 m diameter, 300 m focal length optic

X-ray Optics Challenge





- **X-ray optics operate at grazing incidence**
  - 300-700 more telescope surface area for a given aperture
  - Precisely figured hyperboloid/paraboloid surfaces
  - **Trade-off between collecting area and precision**
- **State of the art is defined by Chandra**
  - 1 arc sec resolution is ~100 times over diffraction limit
  - Very expensive and heavy
  - Grasp is equivalent to a 30 cm diameter
  - **Polished surface area equal to a 5 m optical telescope!**
- **Constellation-X will give 100 times increase in collecting area**
  - Replicated shells or segments 0.5 kg/m^2 areal density
  - 5-15 arc second optics
  - Grasp is equivalent to a 2 m optical telescope
  - **Polished surface area equals a 35 m optical telescope!**

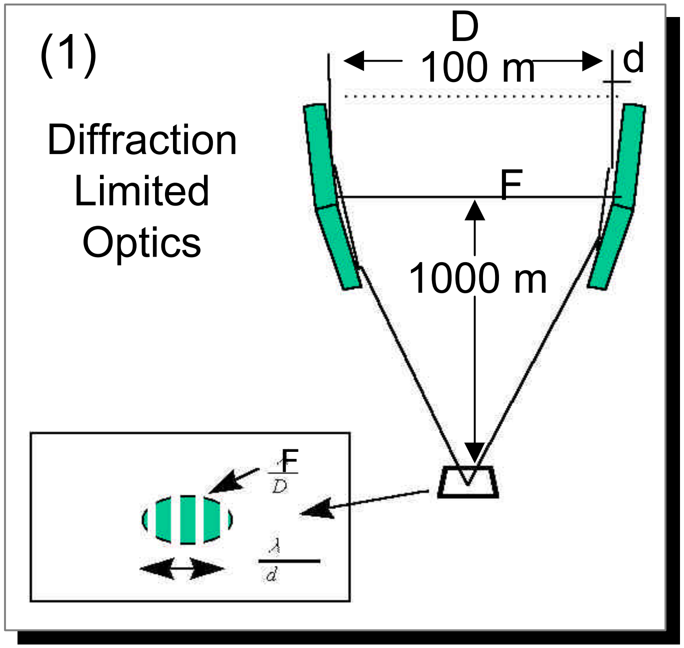
Need a new approach for improved angular resolution!

X-ray Interferometer Implementation Approaches

Two possible approaches to produce X-ray interference fringes

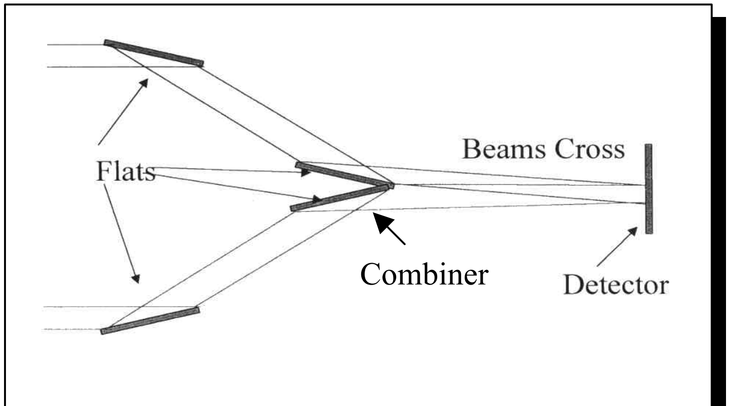
Fizeau: Overlapping two focused beams

- \+ Relatively compact system
- – Require diffraction limited optics
- – Produces nm fringes, magnifier required



Michelson: Use large area flats to combine beams and create fringes

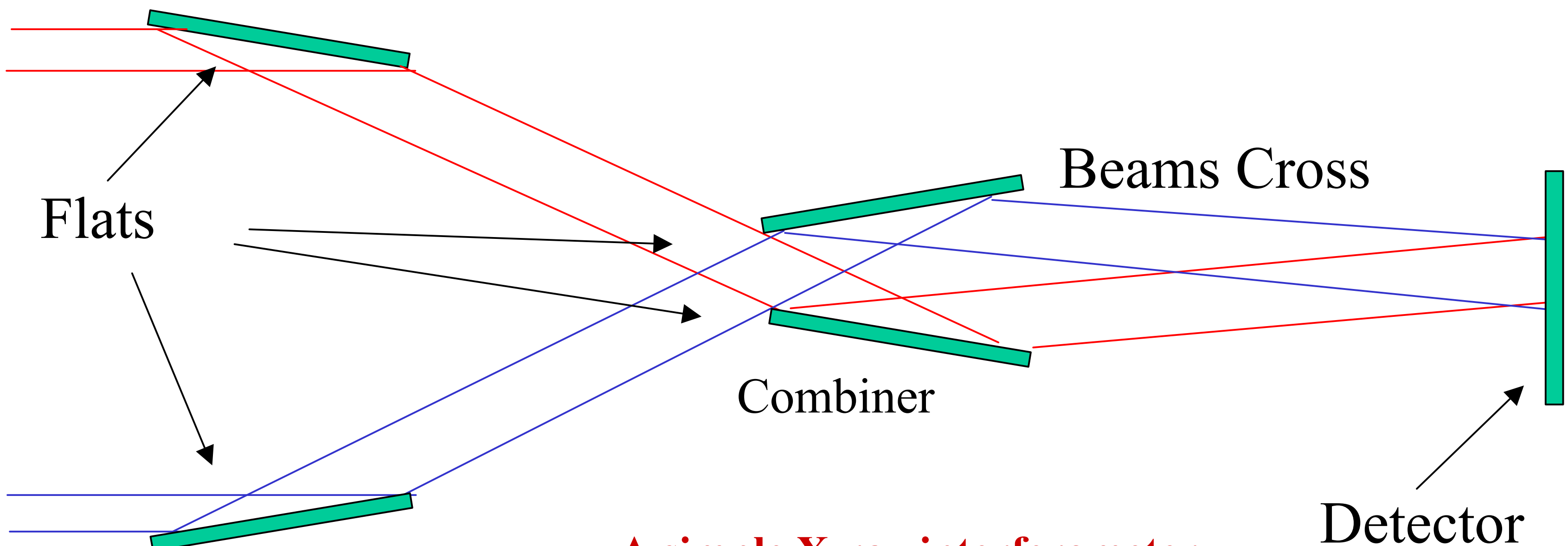
- \+ Flats are much easier to manufacture
- \+ Fringe spacing can be much bigger
- – Very large (1000 km) separation between combiner and detector



Simple Interferometer

Beam Combiner

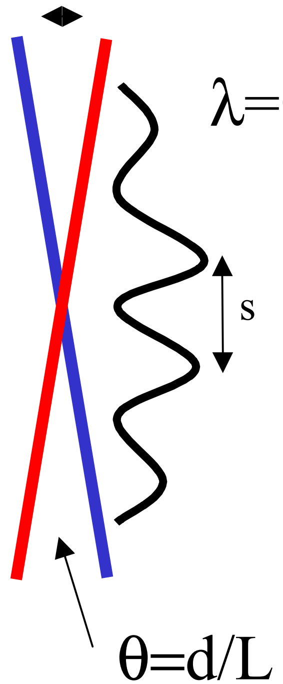
- Use 1/200 grazing incidence flats to steer two beams together
- Beats will occur, even if not focused
- Fringe is spacing function of beam crossing angle



A simple X-ray interferometer

Credit: Webster Cash

Wavefront Interference



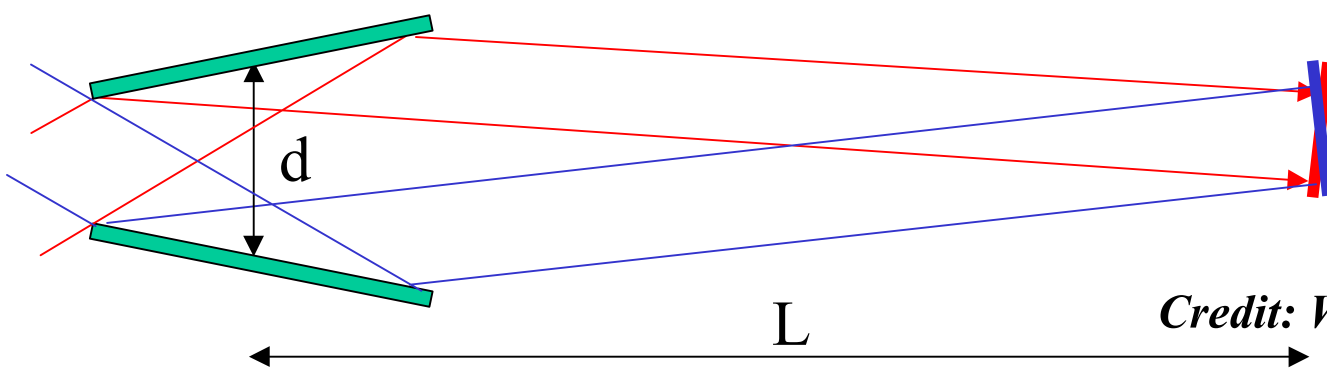
$\lambda=\theta s$ (where s is fringe spacing)

$$s=\frac{Ll}{d}$$

For λ = 1 nm and requirement of s = 5 microns

$$\frac{L}{d}=100{,}000$$

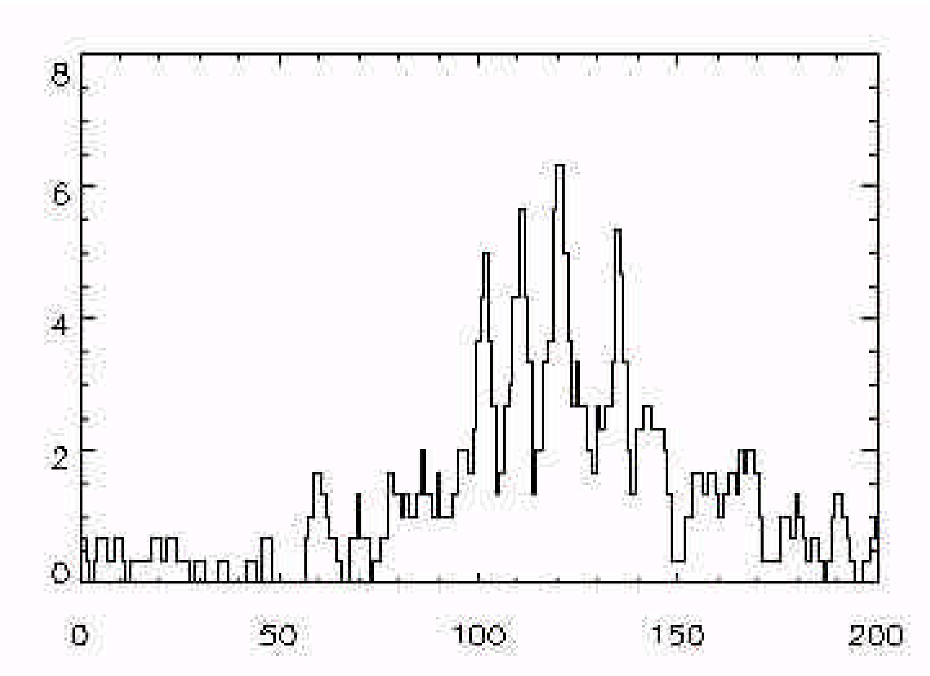
Two Plane Wavefronts Cross



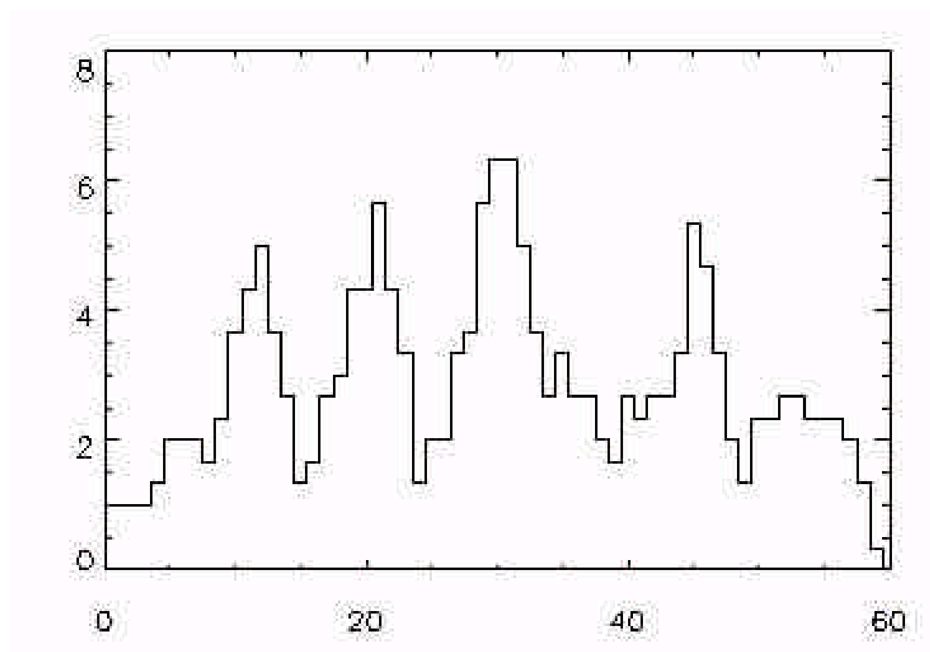
Credit: Webster Cash

Fringes at 1.25 keV !

Test made at MSFC Stray Light Facility



Profile Across Illuminated Region



Expansion of Fringe Region

This lab demonstration system is scalable to an on-orbit telescope!

Credit: Webster Cash and Marshall Joy

Simultaneous Baseline Observatory Design

- Multiple Spacings and Rotation Angles Needed Simultaneously to Sample UV Plan
- 32 flats (300 × 10 cm) held in phase
- Total Area ~1000-10000 cm^2

Resolution @ 1 nm (1.2 keV)

D(m)	*Arc sec*
60 cm	3×10^{-4}
600 m	3×10^{-7}
600 km	3×10^{-10}
600,000 km	3×10^{-13}

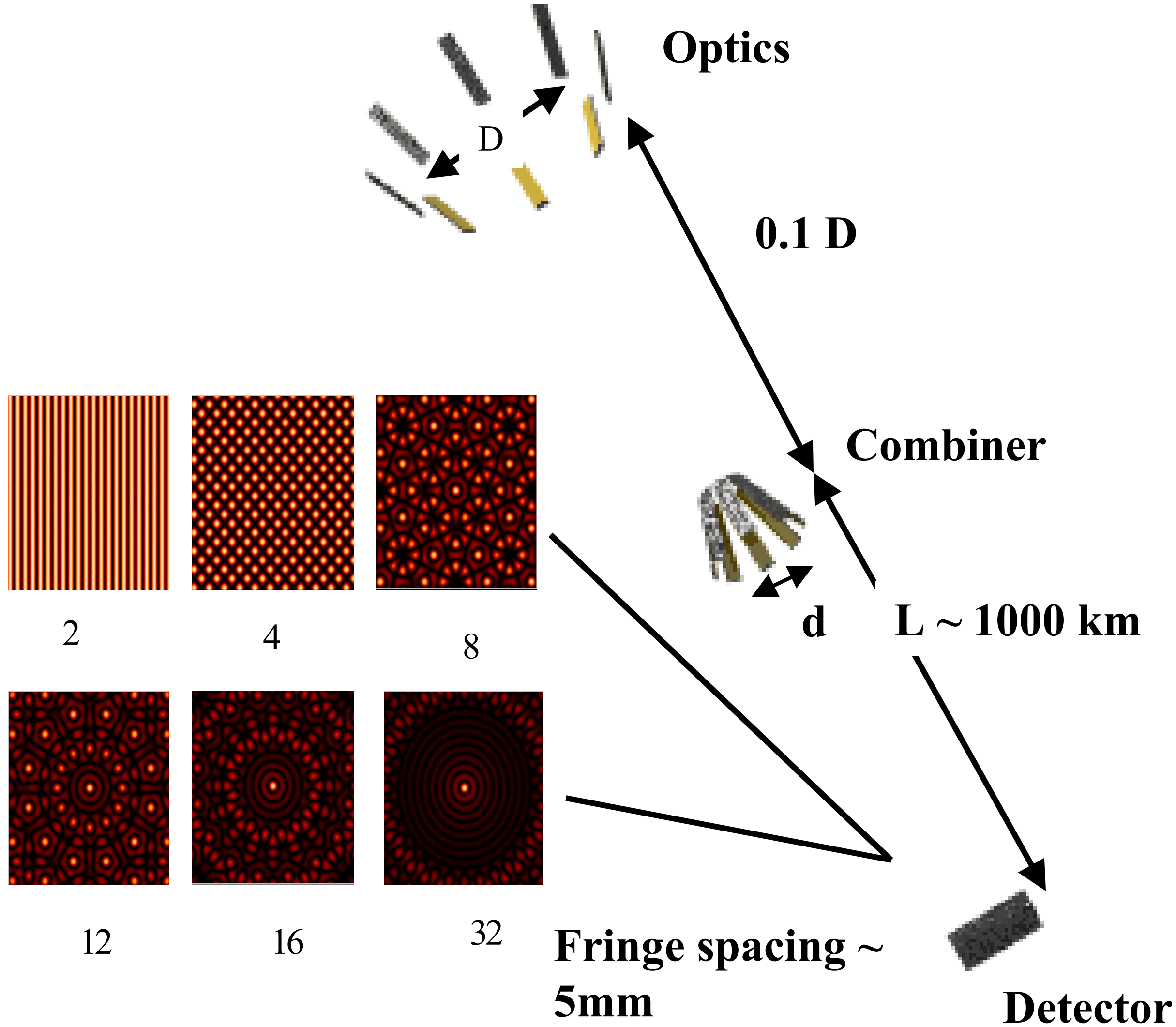
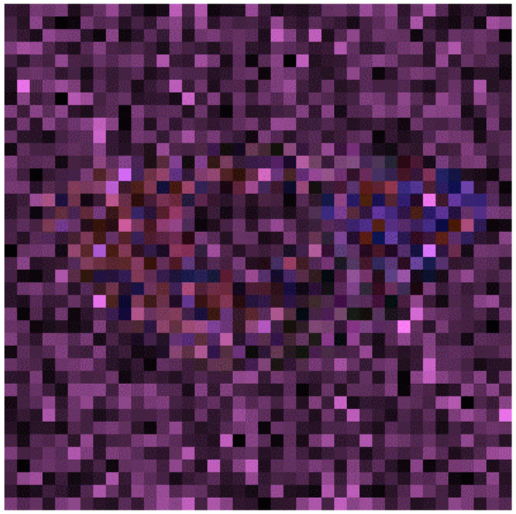
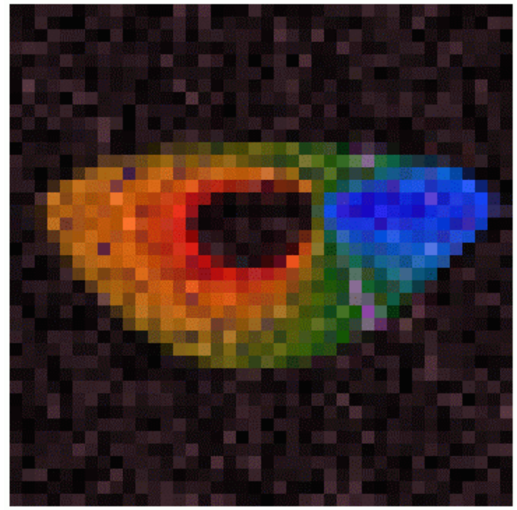


Image Quality VS. S/N Per Baseline

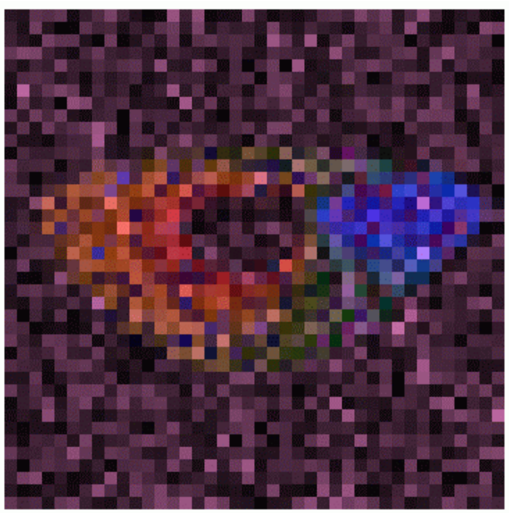


S/N = 0.6
$A_{eff}T = 3$ ´ 10^5

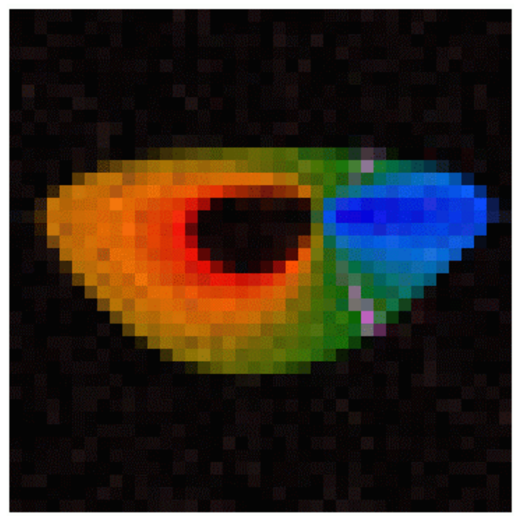


S/N = 6
$A_{eff}T = 3$ ´ 10^7

$F_x = 3$ ´ 10^{-12} erg cm^{-2} s^{-1} keV^{-1}



S/N = 2
$A_{eff}T = 3$ ´ 10^6

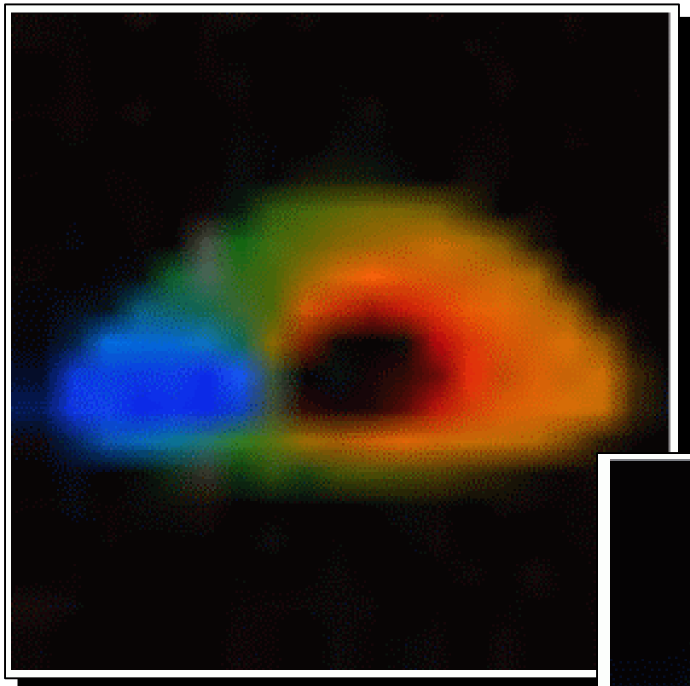


S/N = 20
$A_{eff}T = 3$ ´ 10^8

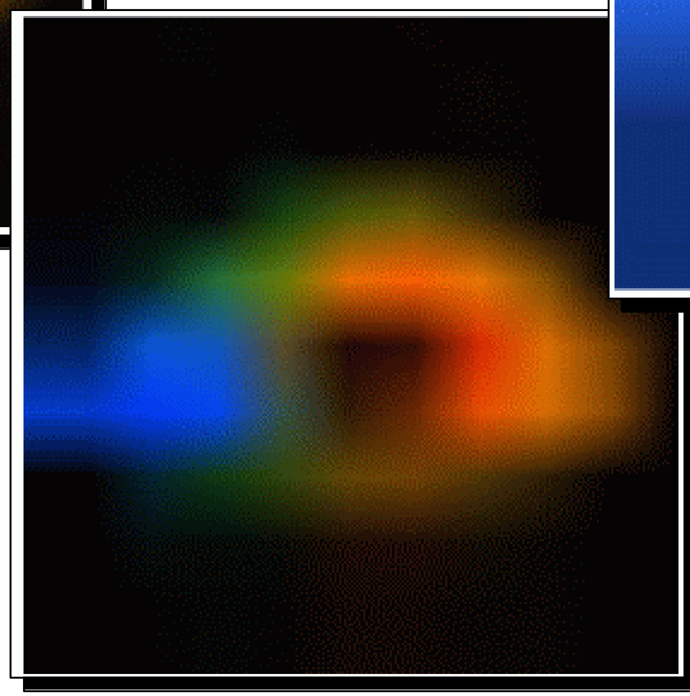
Credit: Chris Martin

Spectroscopic Imaging of a Kerr Black Hole

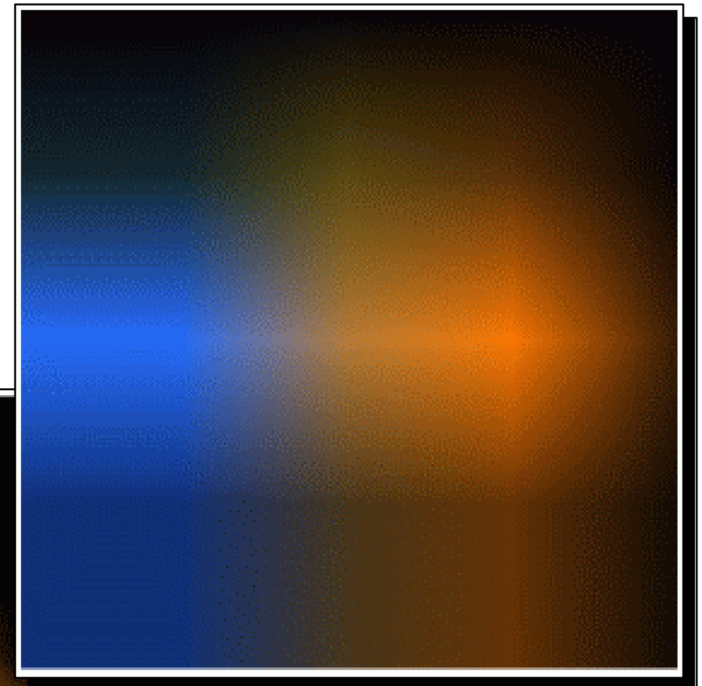
Simulation of Seyfert



2 pixels/(2Rg)



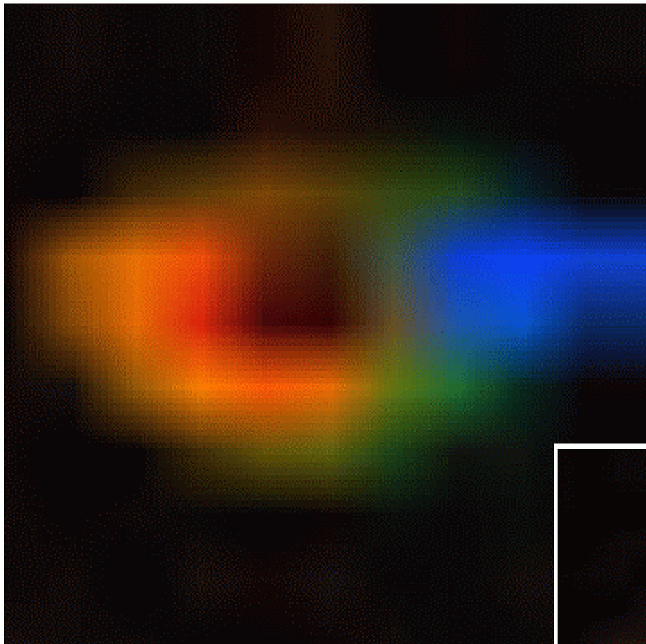
1 pixels/(2Rg)



0.5 pixels/(2Rg)

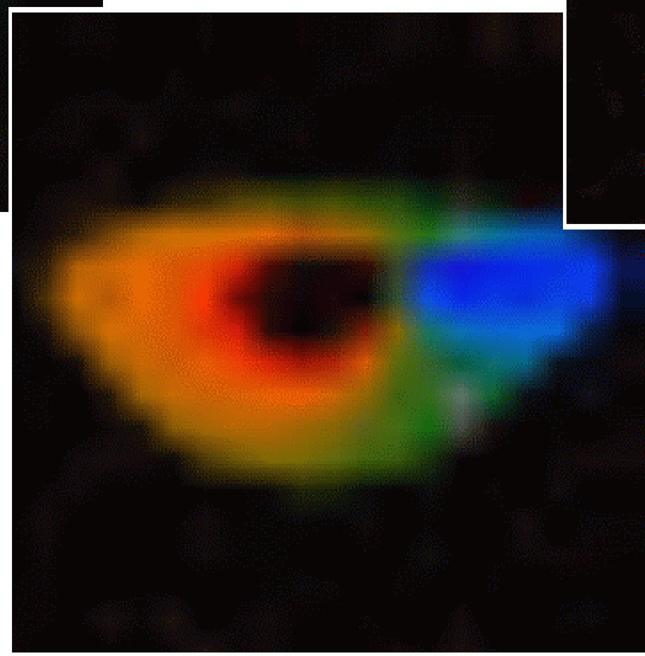
Credit: Chris Martin

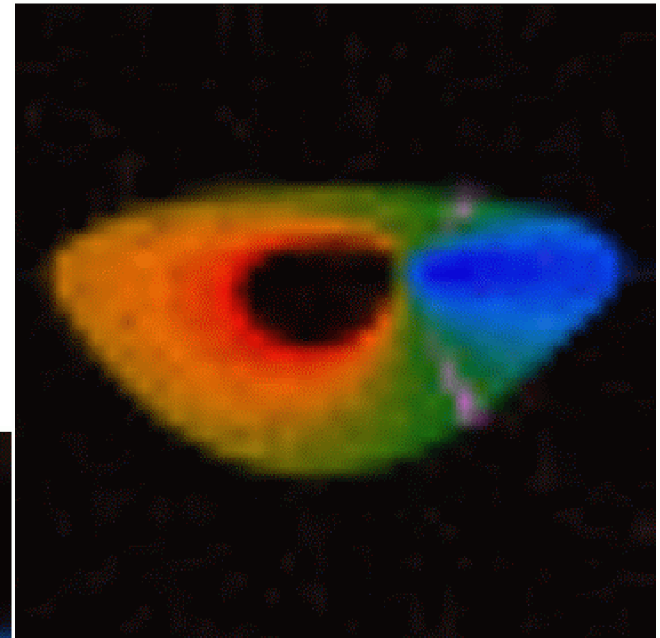
Image Quality VS. Number of Baselines



10 ´ 10 BL

20 ´ 20 BL



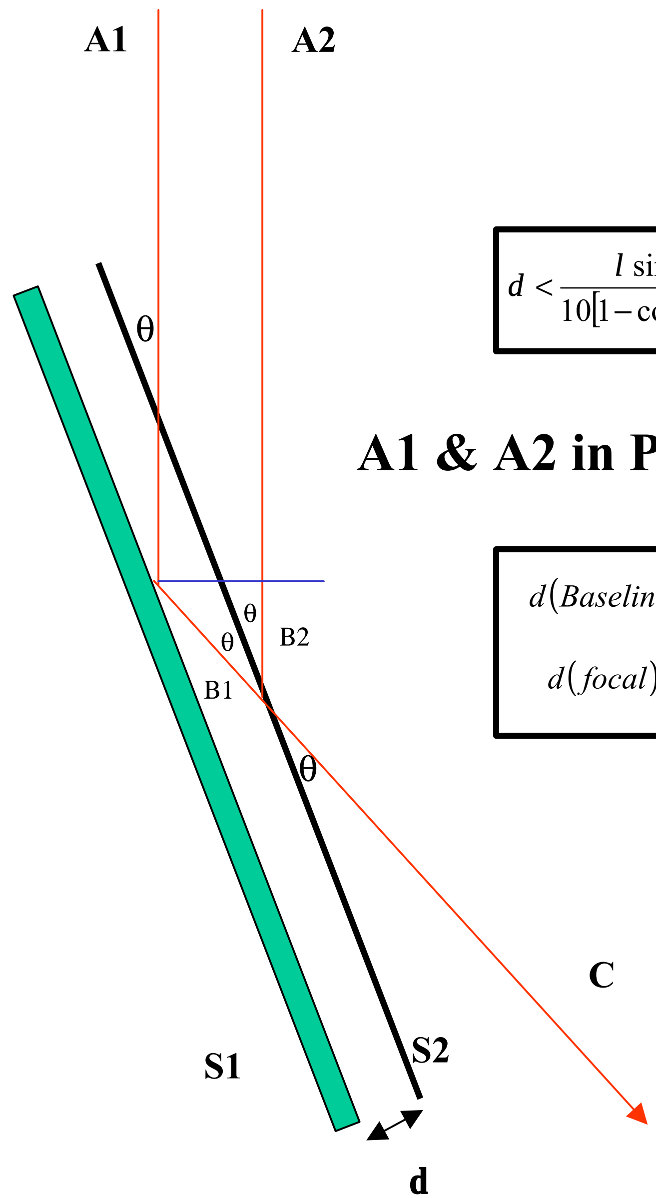


40 ´ 40 BL

Note: constant max baseline, increasing source size

Credit: Chris Martin

Tolerances



$$d < \frac{l \sin q}{10[1-\cos(2q)]}$$

A1 & A2 in Phase Here

$$d(Baseline) < \frac{l}{20q}$$
$$d(focal) < \frac{l}{20q^2}$$

- **At grazing incidence the tolerences required are reduced by ~50**
- **Tightest Tolerance is Separation of Entrance Apertures**
  - d = λ/20θ for tenth fringe stability
  - At 1keV and 2deg, d=1.7nm
  - At 6keV and 0.5deg, d=1.1nm
- **This level of stability is similar to those required for optical interferometry**
  - **Good synergy with technology being developed for origins**
- **Another advantage over opitcal is that X-ray detectors have intrinsic energy resolution**

Tolerances for an X-ray Interferometer

Assume 1nm (10Å) Radiation, 2 degree graze

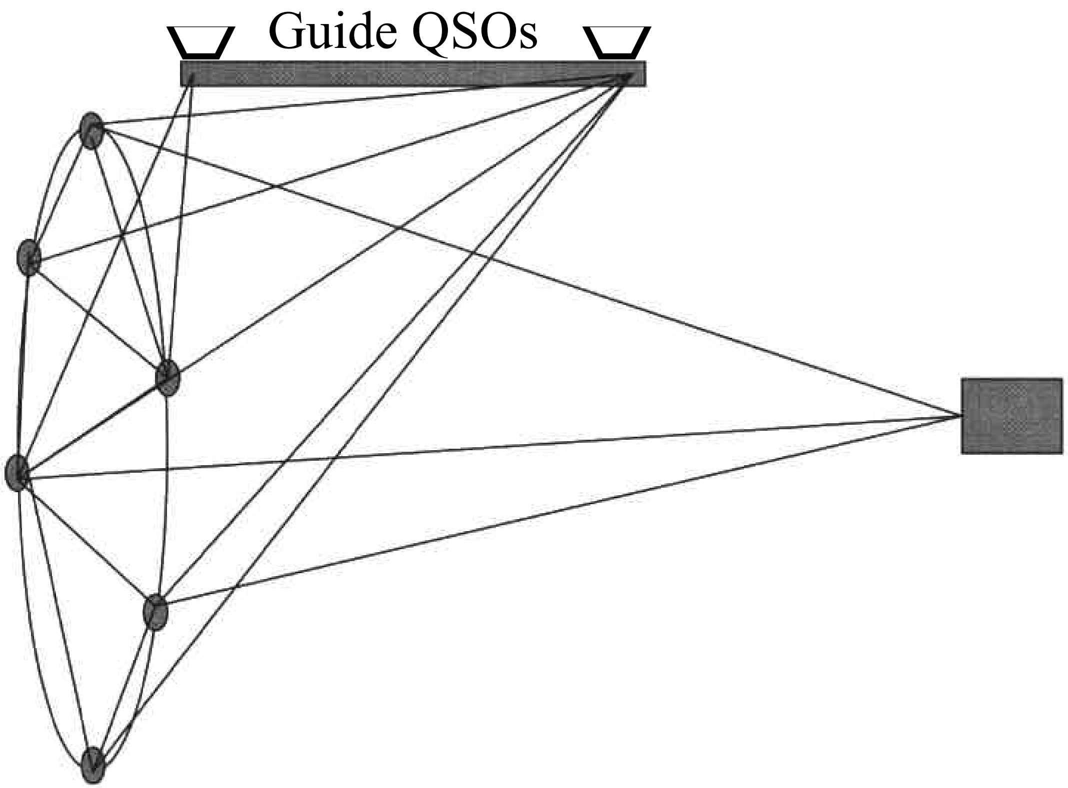
Resolution Arcseconds	**10^{-4}**	**10^{-5}**	**10^{-6}**	**10^{-7}**
Baseline (m)	**1**	**10**	**100**	**1000**
Mirror Size (cm)	3 x 100	3×100	3×100	3×100
Position Stability (nm)	20	20	20	20
Angular Stability (arcsec)	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Figure	$\lambda/100$	$\lambda/200$	$\lambda/200$	$\lambda/200$
Polish (Å rms)	20	20	20	20
Angular Knowledge (as)	3×10^{-5}	3×10^{-6}	3×10^{-7}	3×10^{-8}
Position Knowledge (nm)	2	2	2	2
Field of View (Pixels)	20×20	20×20	1000×1000	1000×1000
E/ΔE Detector	20	20	1000	1000

Pathfinder *MAXIM*

Notes:

- **Angular stability is for individual mirrors relative to target direction.**
- **Only the Angular Knowledge requirement grows tighter with baseline, but this is achieved by a (fixed) 2nm relative position knowledge over a longer baseline.**
- **Absolute positioning remains constant as interferometer grows but does not get tighter!**

Tie X-ray Interferometer to Optical Guide Interferometer



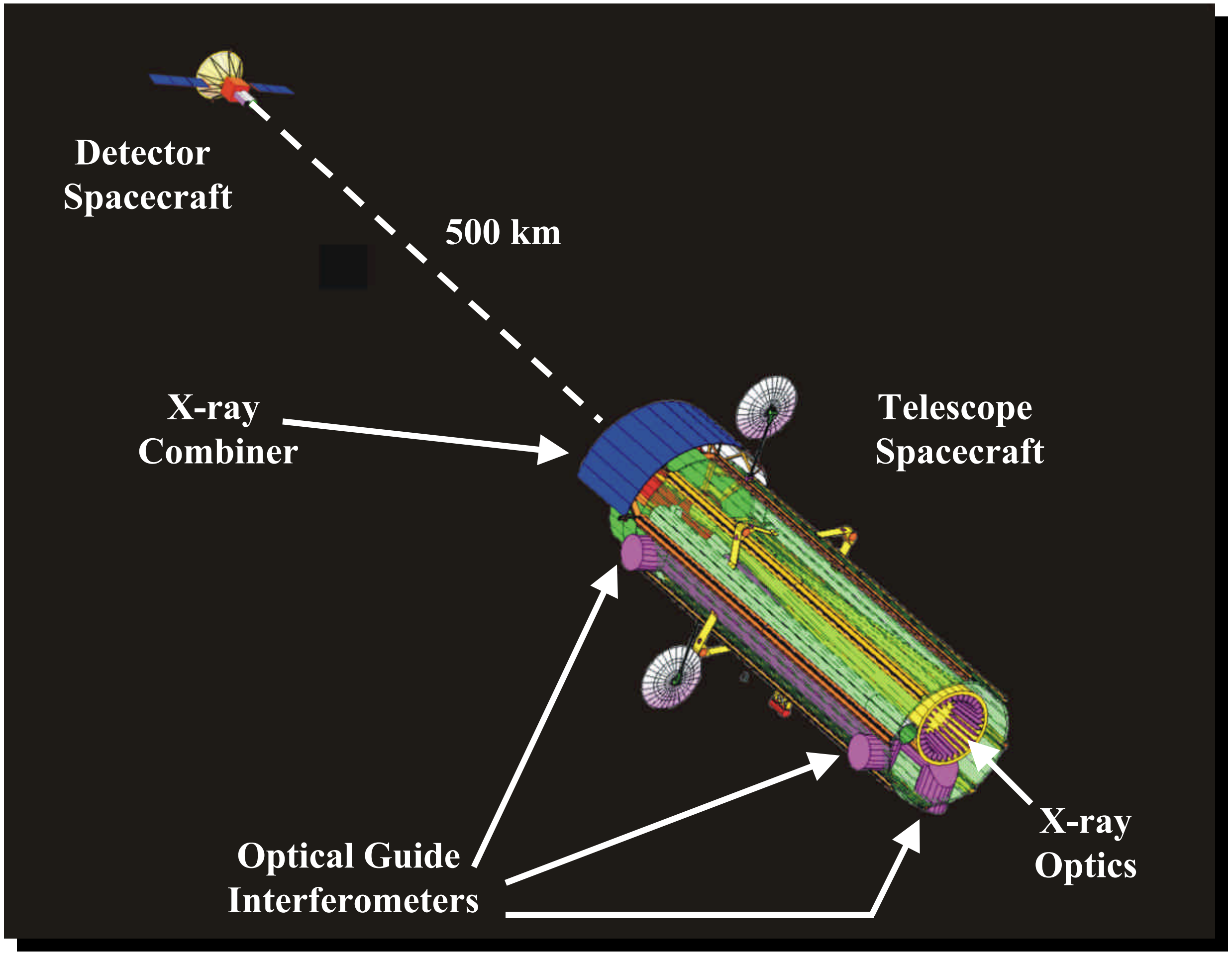
Optical interferometers tied to array of X-ray collectors with laser truss

- Long baselines (>100m) require multiple spacecraft flying in formation with 20 nano-meter stability and 2 nano-meter knowledge
- Similar problem for the planet finder
- Aspect from optical interferometer
  - 1 mas with a 40-50 m baseline as star/QSO tracker
  - Based on Space Interferometry Mission (SIM)

Credits: Mike Shao

We need an Intermediate Step: MAXIM Pathfinder

MAXIM pathfinder will:



Two formation-flying spacecraft

- Prove X-ray interferometry in space
- 100 milli-arc sec (1-2 m baseline)
- Image
  - Coronae of nearby stars
  - Supernovae in M31
  - Jets in SS433
  - AGN broad line region
- Candidate mission in SEU mid-term roadmap
  - Flight around 2015?
- Pathfinder for full up MAXIM to come 5-10 years later with 100 m to 1 km baseline.

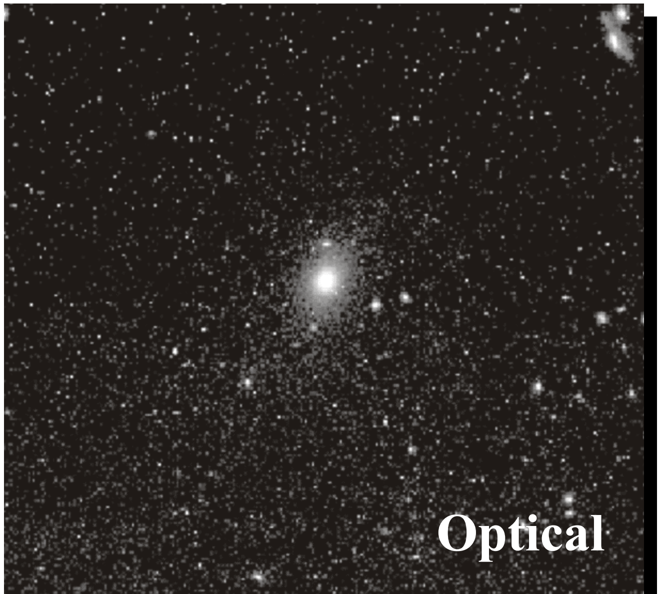
Prospects for X-ray Interferometry

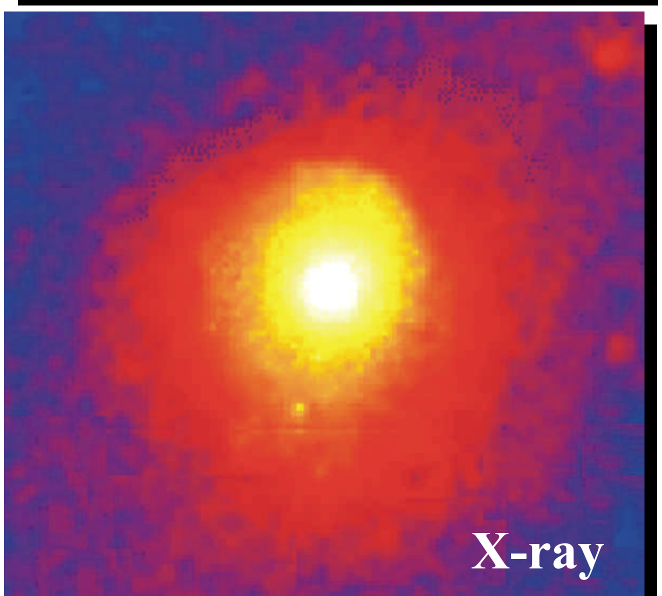
- X-ray interferometry has radical scientific potential and while technologically challenging, is feasible
- Tolerances and metrology are comparable to those needed for SIM
- The laboratory Proof of Concept exists today

Next Steps:

- Chandra and Constellation-X to find best targets and optimize MAXIM parameters (baseline, area)
- Program of precision X-ray optics development $\lambda/200$
- Formation flying and precision metrology
- Pathfinder X-ray interferometry mission with 100 μas by 2015
- MAXIM 0.1-1.0 μas by 2020-2025

Large Scale Structure (LSS)
X-rays are Central to the Problem

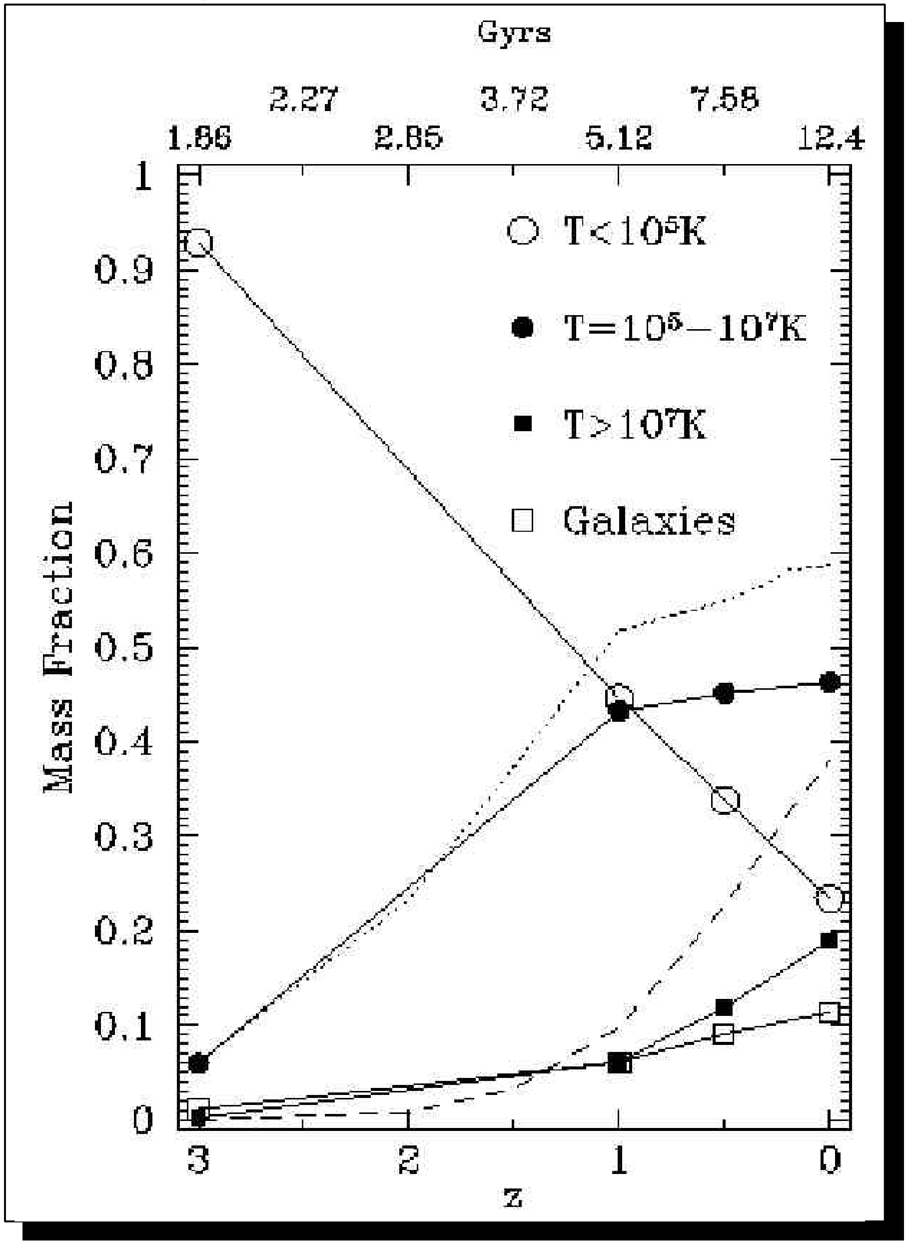




As the Universe evolved, structure appeared: stars, galaxies, & clusters of galaxies

- **Clusters of galaxies are the largest and most massive virialized objects in the Universe!**
  - Hot X-ray emitting gas makes up the majority of the baryons
  - Most of the visible "metals" are in the same gas
  - ***Dark matter holds it together***
  - **X-rays trace the baryons and the dark matter**
- **The epoch of formation of these structures depends on the cosmological parameters and the nature of dark matter**
  - In a cold dark matter models clusters come after galaxies, in hot dark matter it is vice versa
  - Hot dark matter ruled out by the observations

Where are the Missing Baryons?

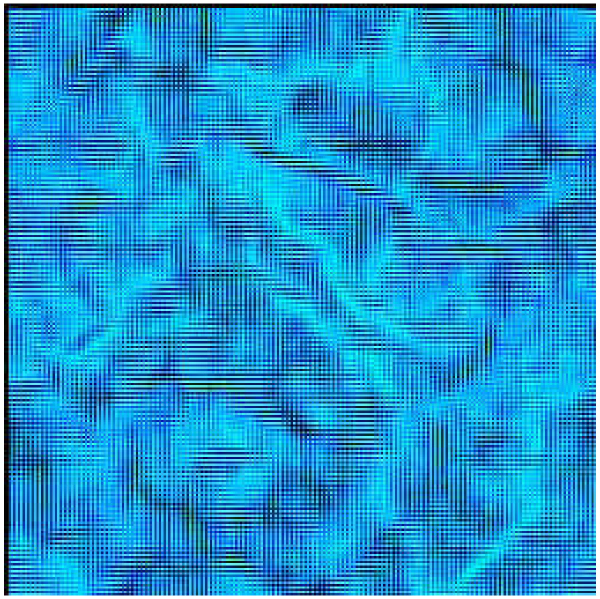


- **Fukugita, Hogan, & Peebles made a local Universe Cosmic Baryon Budget**
  - They could account for only 20% of the baryons in known objects
  - Where is the local Lyman-α forest?
- **Detailed theoretical work on the formation of large scale structure (e.g., Cen and Ostriker 1999) show that**
  - Most of the "unseen" baryons should lie in a dilute hot million degree K gas
  - Best seen via X-ray emission and absorption
- **Most of the matter in the Universe is hot**
  - Only visible as the hot X-ray emitting gas in groups and clusters of galaxies.

Formation of Structure

- Using a cosmological hydrodynamic code we can follow the evolution of the Universe ($\Omega_o = 0.37$, $\Omega_b = 0.05$, $\Lambda = 0.63$, $h = 0.7$)

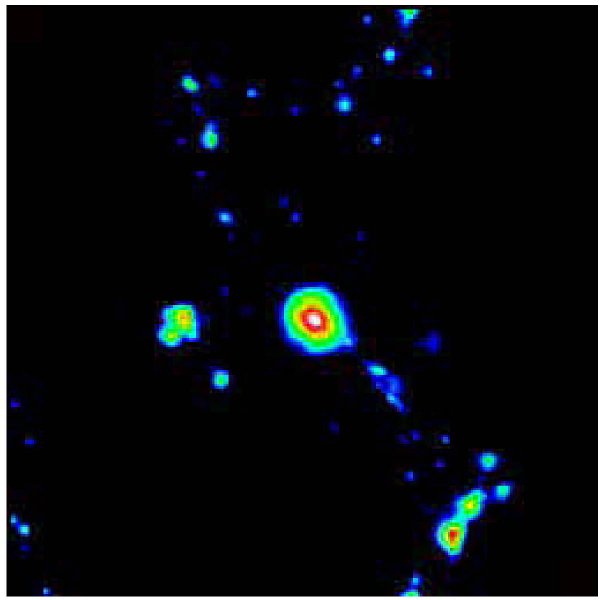
Density



8 megaparsecs deep

X-ray Luminosity

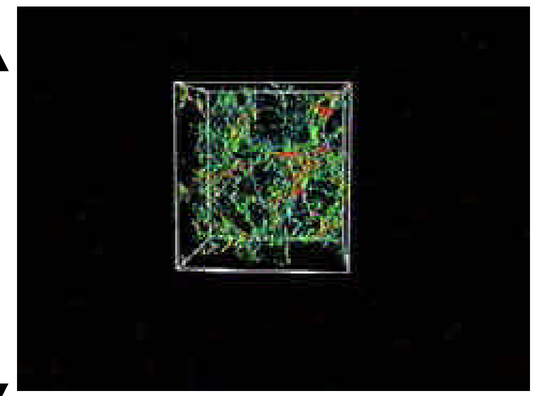
32 megaparsecs



Credit: Bode, Cen, Ostriker, and Xu

Temperature

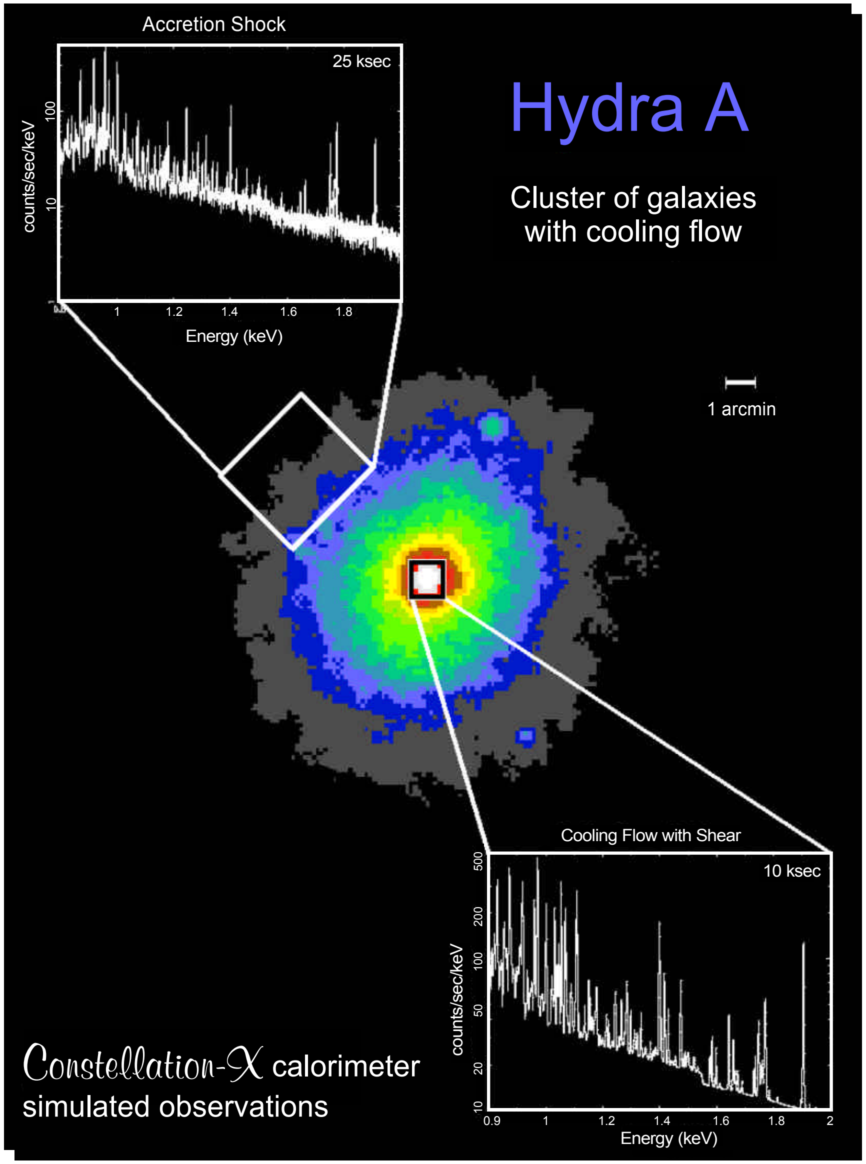
100 megaparsecs



Credit: Cen & Ostriker

The Universe as a whole gets hotter as it evolves, from gravitational and shock heating of the collapsing gas - it lights up in X-rays!

When Were Clusters of Galaxies Formed and How Do They Evolve?

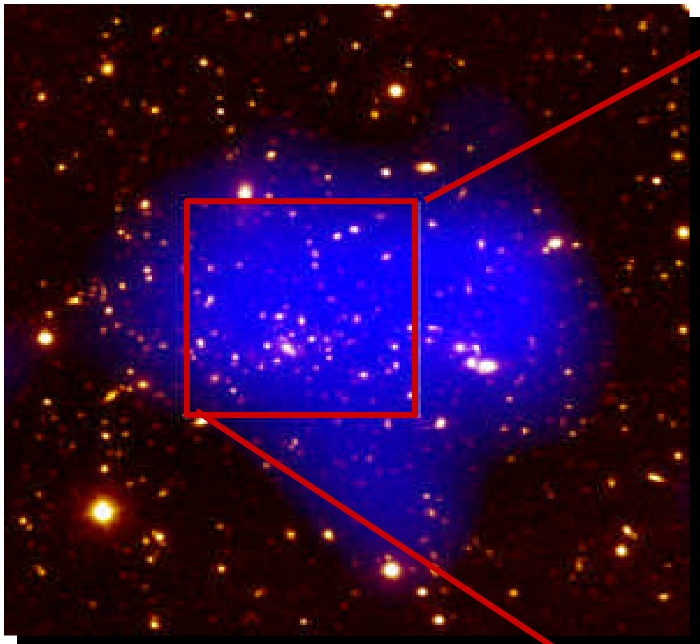


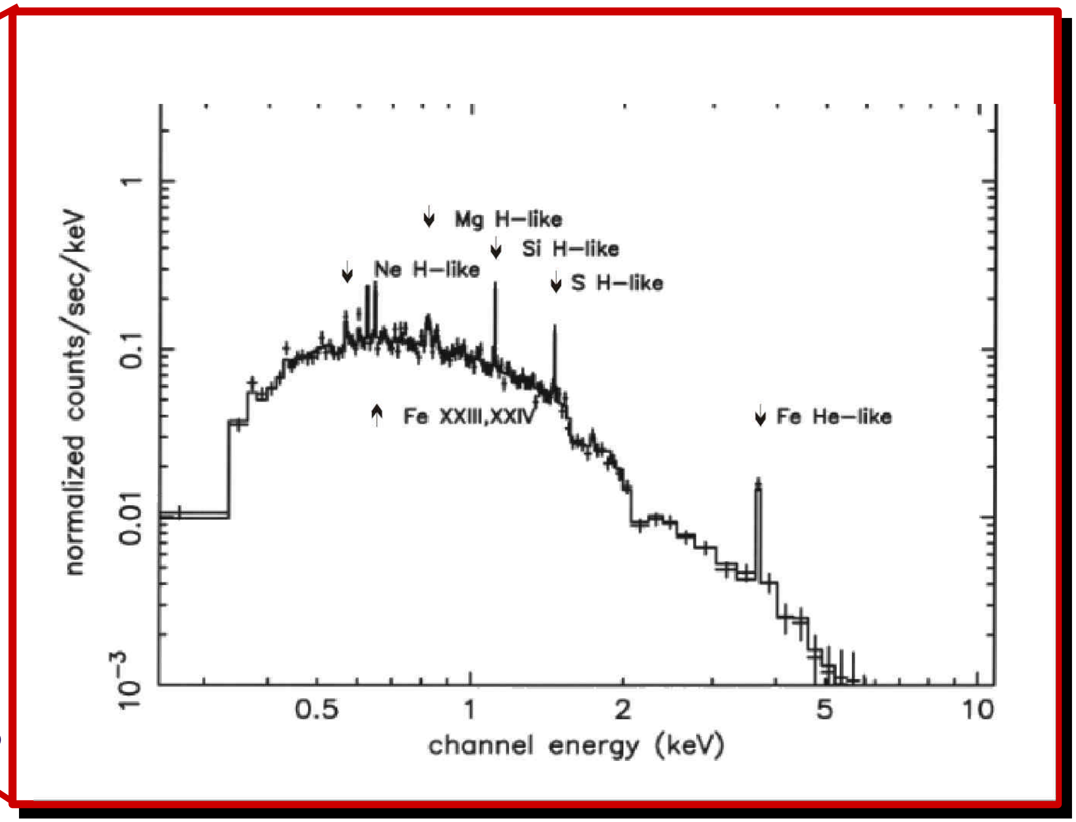
Constellation-X observations of clusters and groups of galaxies essential for understanding structure, evolution, and mass content of the Universe

- Observe epoch of cluster and group formation and determine changes in abundances, luminosity, temperature, and size *vs* redshift
- Absolute distances to arbitrary redshifts using S-Z effect
- Map velocity profiles, probing dynamics of mergers and measuring distributions of luminous and dark matter

Constellation-X Observations of High z Clusters

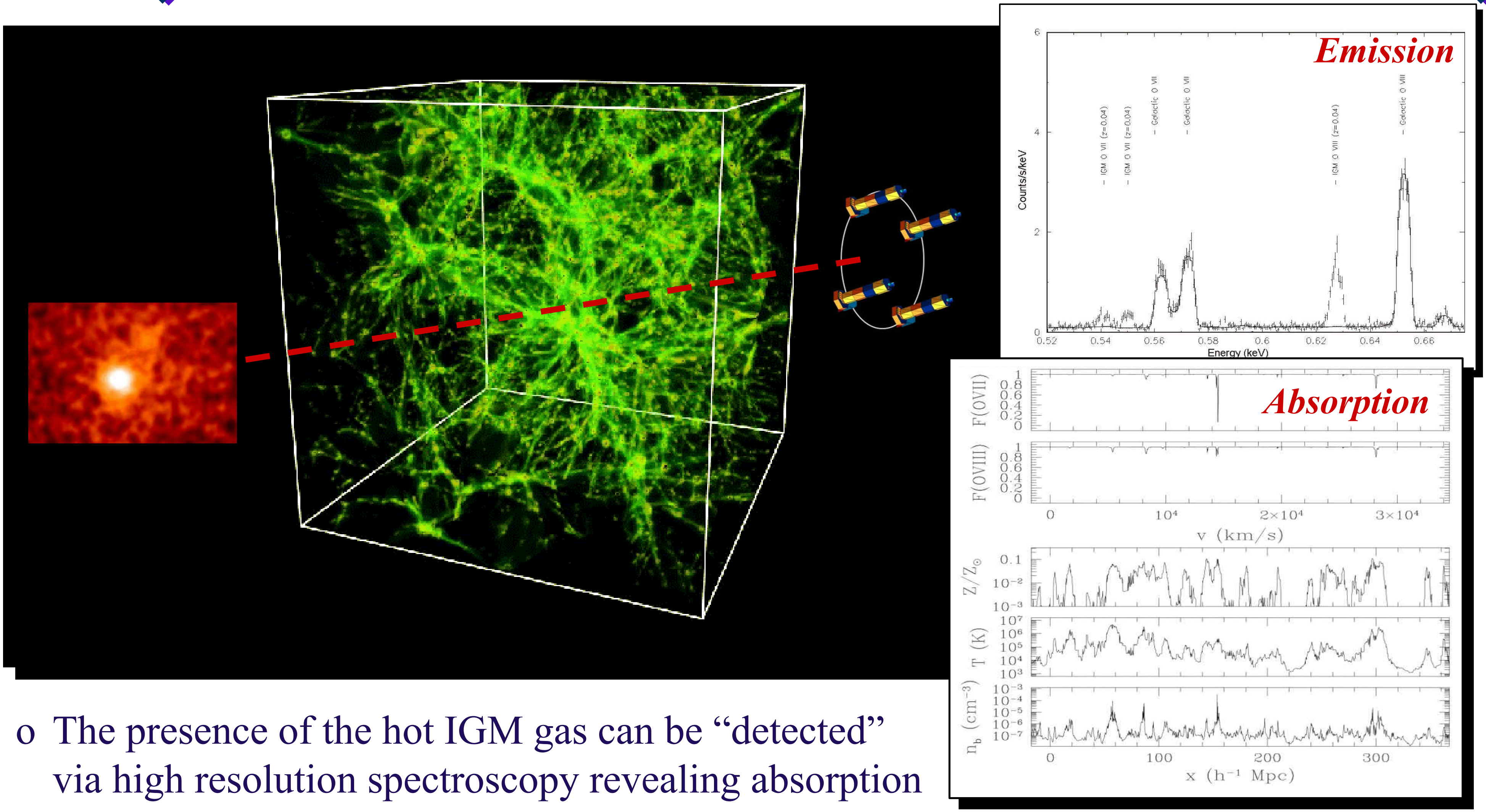
A simulated 50,000 s Constellation-X exposure of a cluster at z=0.8:





- **Abundances are determined to 10% accuracy for Si, S, and Fe and 20% for Ne and Mg**
- **The Sunyaev-Zeldovich Effect provides distances independent of cosmic distance ladder**
  - Constellation-X will provide necessary temperatures to combine with Chandra and CMB measurements
  - Constraints on "Λ"

Where Are the “Missing Baryons” in the Local Universe?



- The presence of the hot IGM gas can be “detected” via high resolution spectroscopy revealing absorption lines of IGM metals against the spectrum of background quasars
- Constellation-X will be able to probe up to 70% of the hot gas in groups and clusters of galaxies at low redshifts through OVIII resonant absorption

The Universe is Hot!

- **X-ray Astrophysics is central to understanding the Structure and Evolution of the Universe**
  - In the current epoch, most of the Universe is hot
  - Most of the metals are in the hot phase
  - X-ray emission is the least biased way to trace the large scale structure: it traces the potential well of the dark matter
- **Constellation-X will determine**
  - When groups & clusters of galaxies formed and their evolution
  - Search for and determine the nature of the IGM for $z < 1$
  - History of chemical enrichment in the Universe
  - Distance scale of the Universe (combined with S-Z & CMB)

Conclusions

- **X-ray interferometry to image a black hole is feasible**
  - But is well beyond current capabilities and requires major technology program
- **Ground work is needed to select the best targets and optimize the MAXIM parameters (area, baseline, energy band)**
- **The path to image a black hole will enable technology that will provide answers to many other interesting science problems**

NASA X-ray and Gamma Ray Future Missions

Near Term (in strategic plan for new starts 1999-2007)

- **Swift: 2003**
  - **Panchromatic, rapid response Gamma Ray Burst mission**
- **GLAST: 2005**
  - **GeV Gamma Ray Survey mission**
- **Constellation-X: 2008-2010**
  - **Large area spectroscopy mission**

Mid Term (candidates for new starts 2008-2012)

- **MAXIM Pathfinder**
  - **First X-ray Interferometry Mission (100 micro arc sec)**
- **HSIM**
  - **Nuclear Line studies out to Virgo cluster using hard x-ray optics**
- **EXIST**
  - **Hard X-ray Survey**

Vision Missions (launch > 2020)

- **MAXIM**
  - **Black Hole Imager (Micro arc sec Interferometer)**
- **ACT**
  - **Very Large Area Compton Telescope for Nuclear Line Science**
- **Generation-X**
  - **Early Universe Observer (100 times Constellation-X)**